CMS results on jet quenching with jets and heavy flavor mesons

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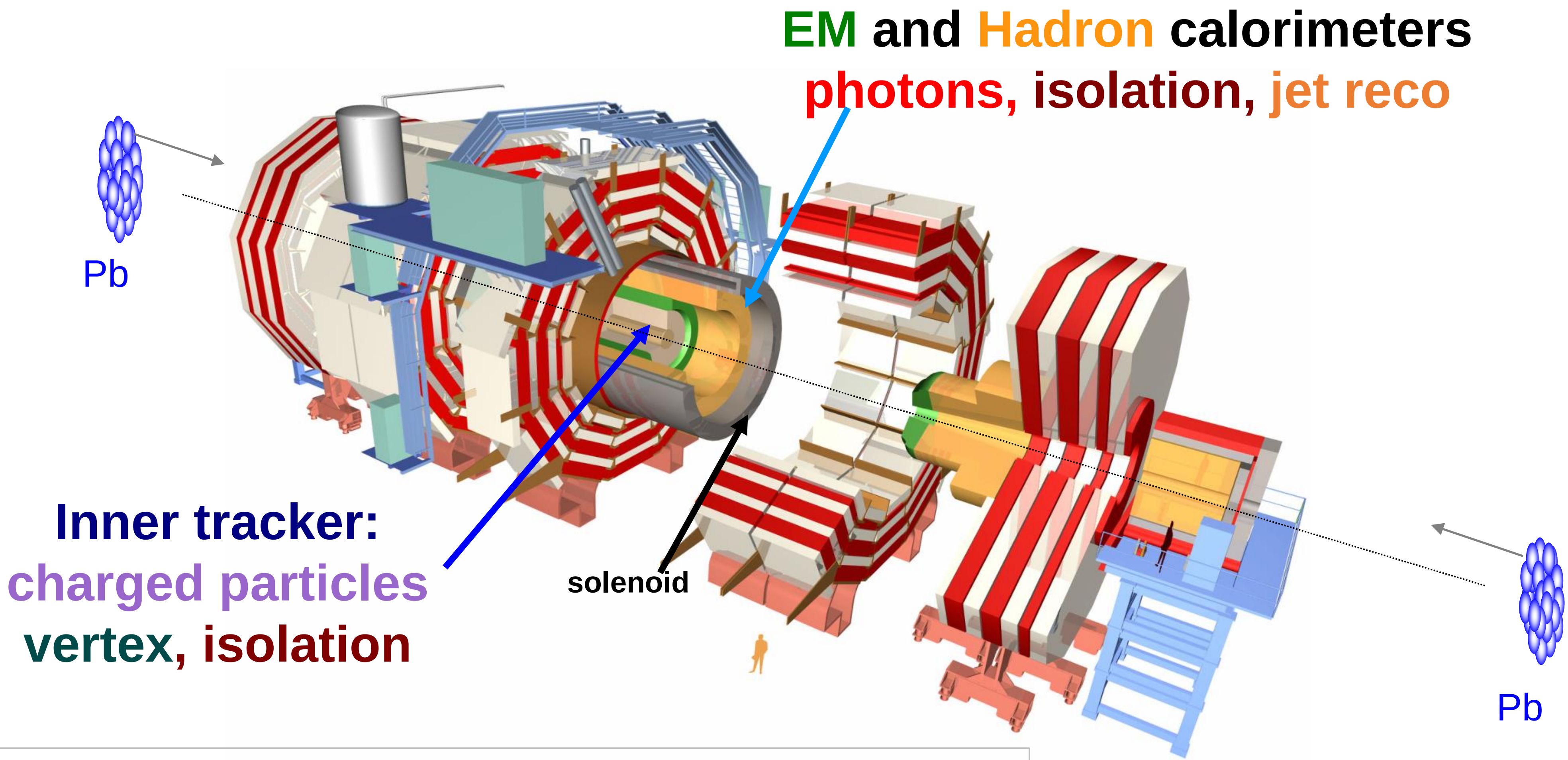
Massachusetts Institute of Technology
(For the CMS collaboration)

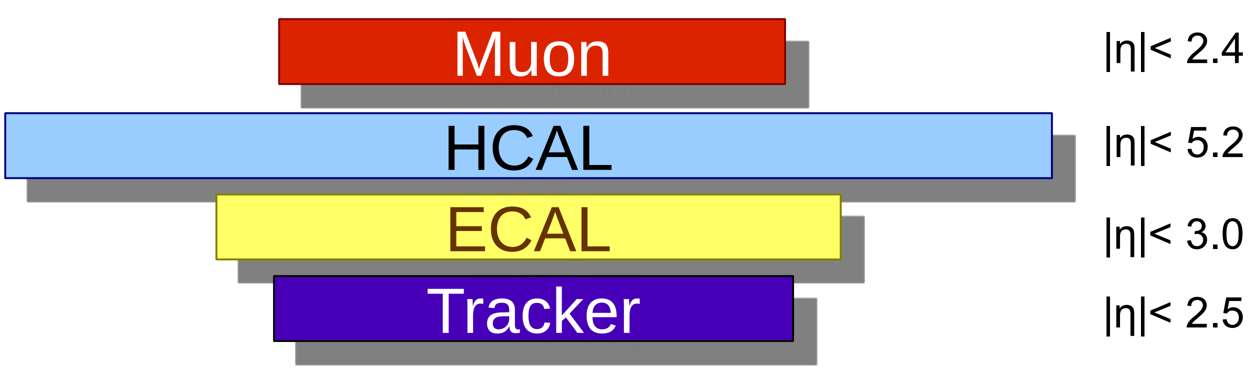
High pT Physics in the RHIC-LHC Era

BNL, USA

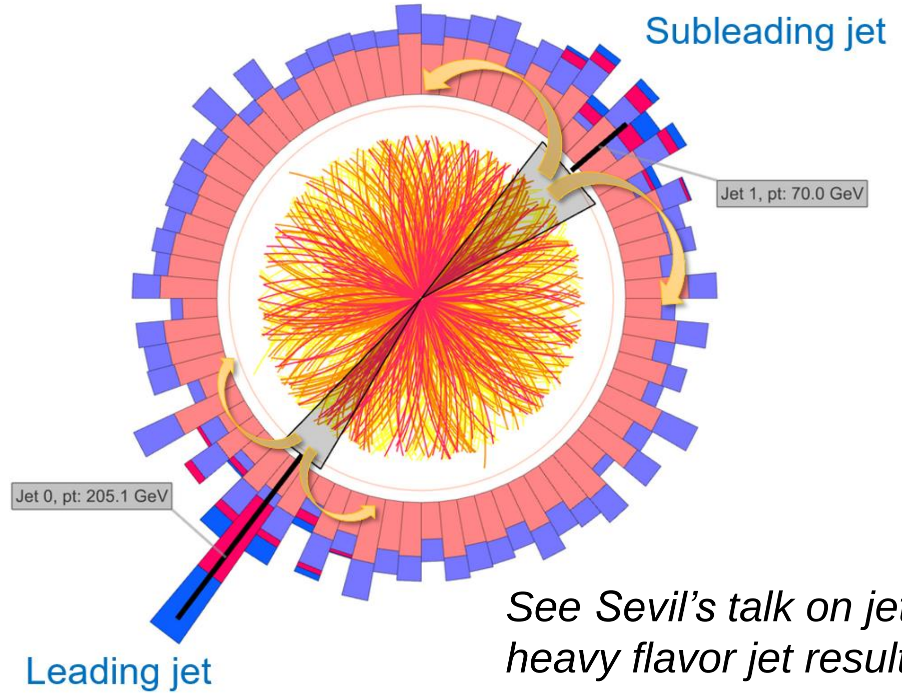
12-15 April, 2016

The CMS Detector



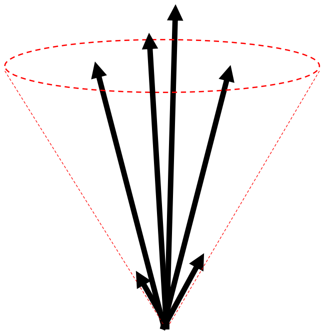


Recent CMS Results on Jet Quenching

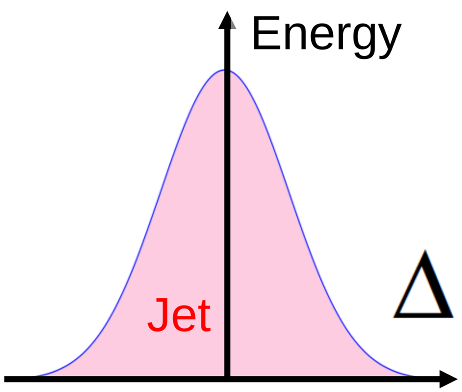


See Sevil's talk on jet spectra and heavy flavor jet results

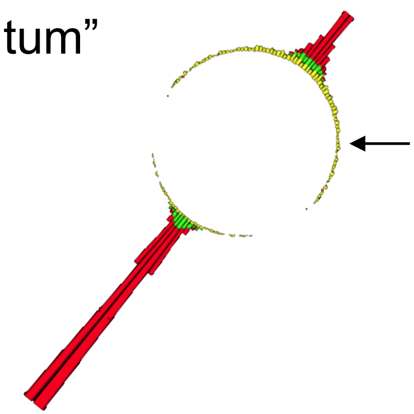
Jet Fragmentation Function:
how transverse momentum is distributed inside the jet cone



Jet Shape:
"the jet energy distribution" as a function of Δ



Quenched Energy Flow:
"angular distribution of the associated transverse momentum"



Flavor Dependence of the Parton Energy Loss
through heavy flavor meson suppression

Recent CMS Results on Jet Quenching

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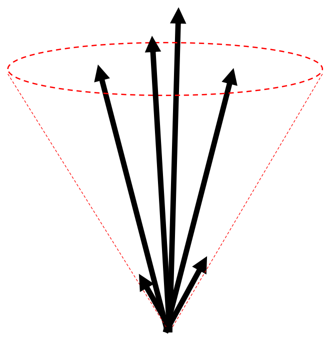

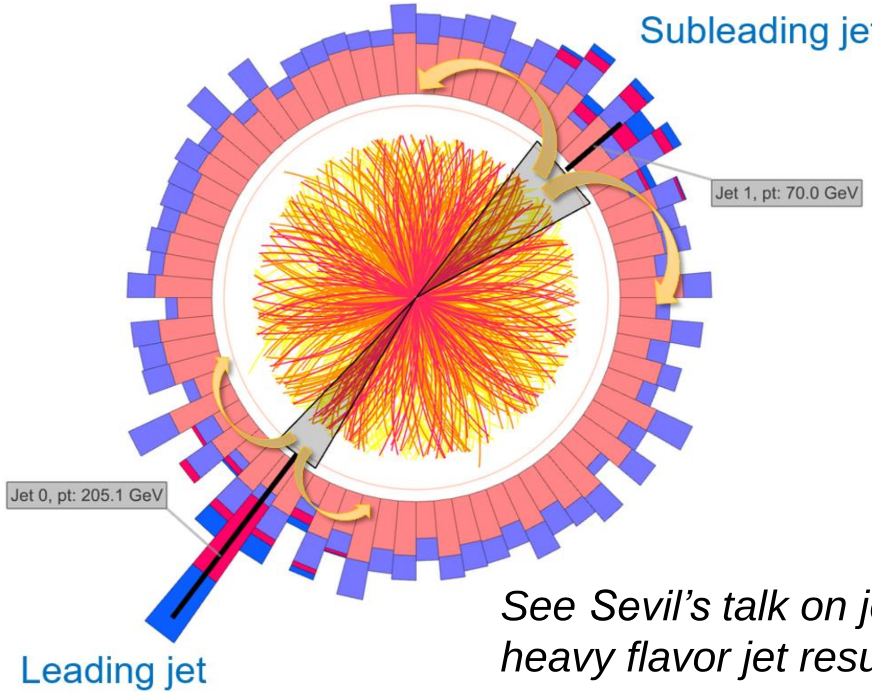

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Flavor Dependence of the Parton Energy Loss
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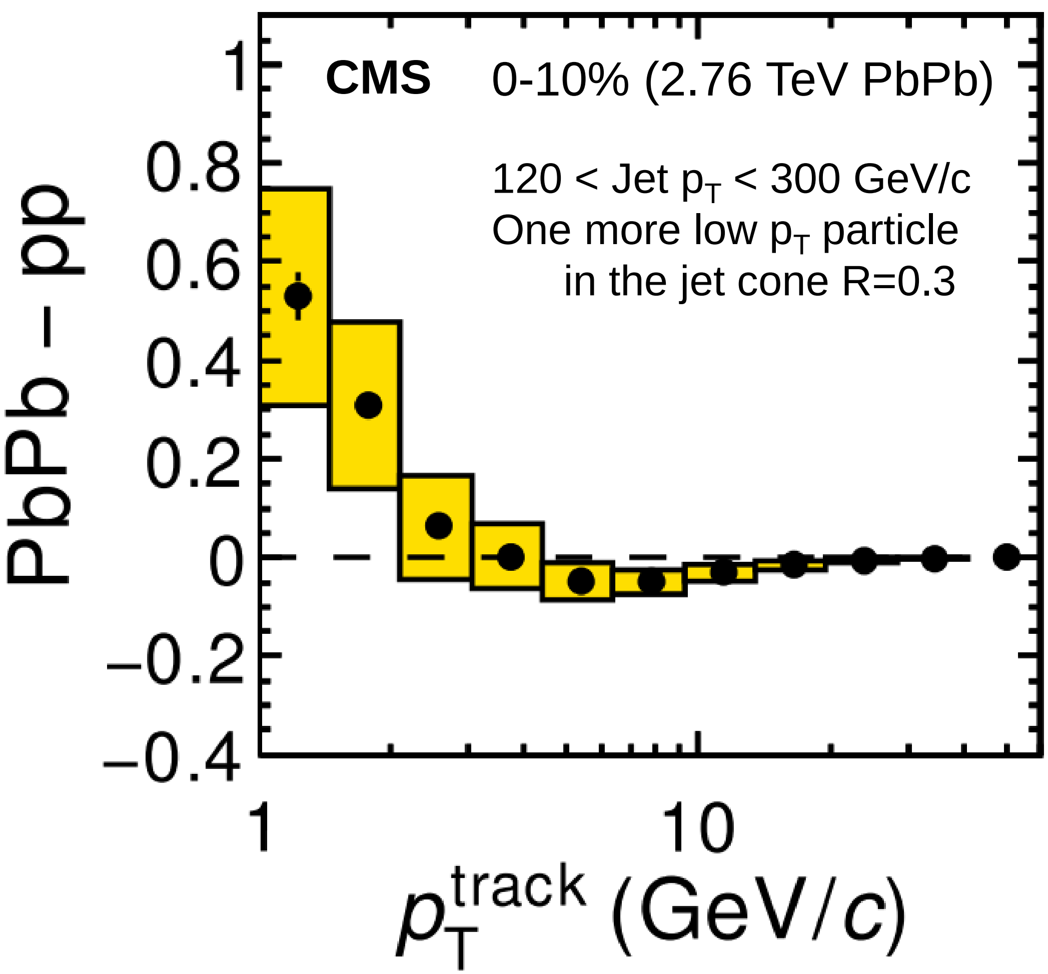
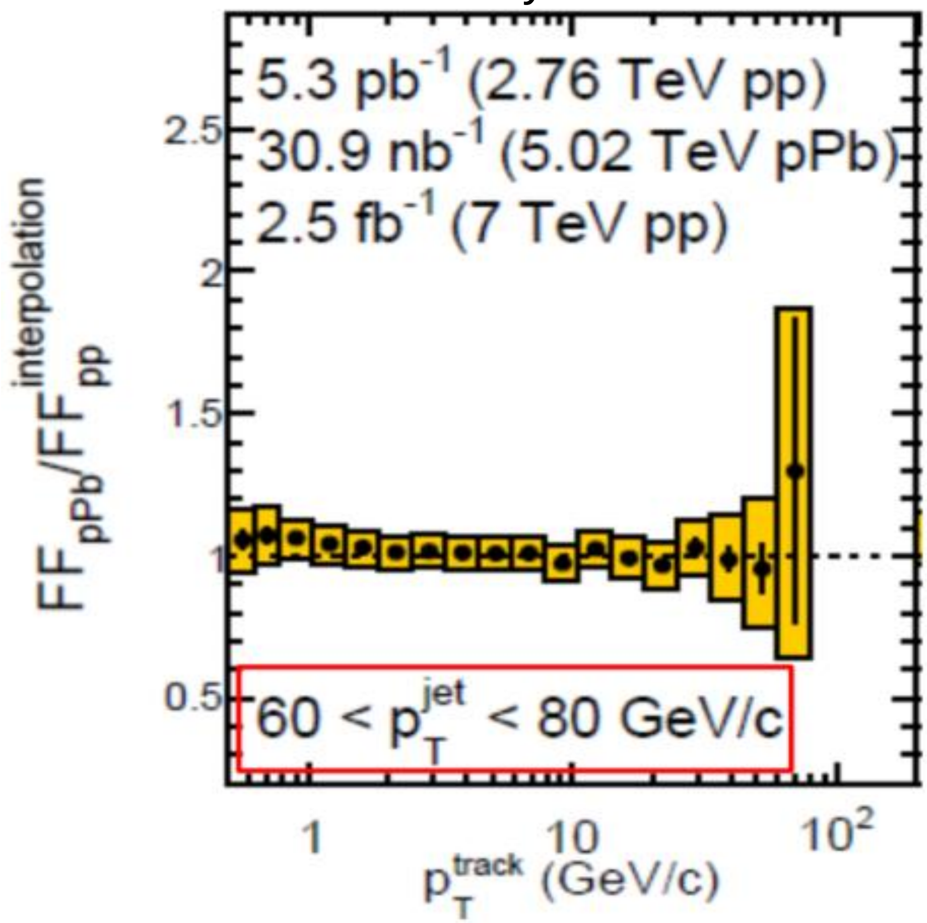
Inclusive Jet Fragmentation Function

Charged particle in the jet cone PbPb - pp



PRC 90 (2014) 024908

CMS Preliminary **pPb / pp**

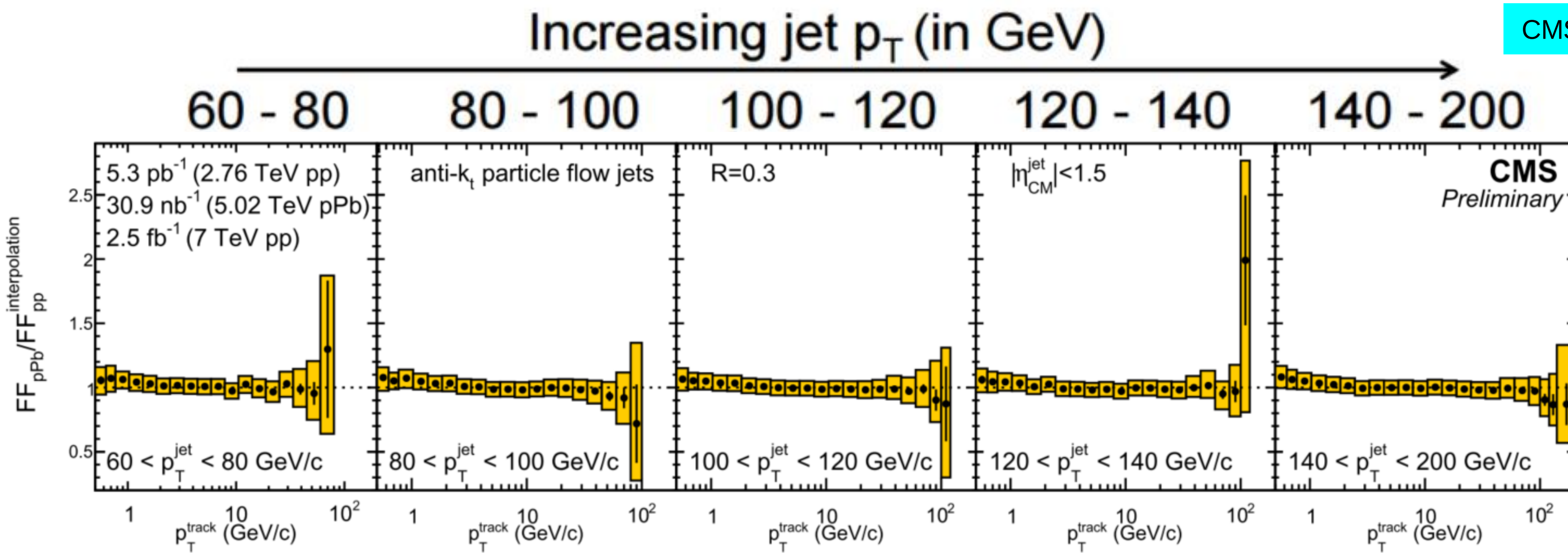


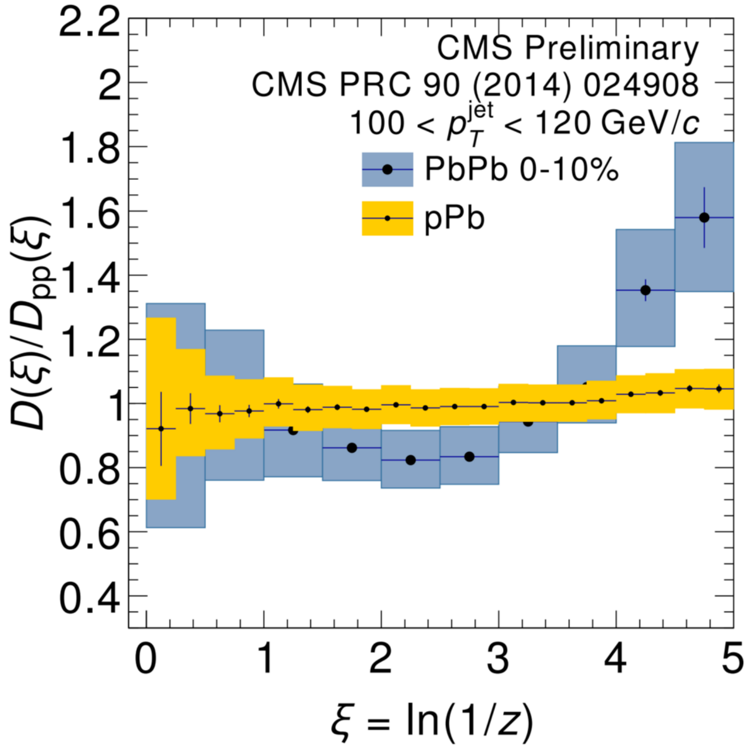
CMS-PAS-HIN-15-004

Jet fragmentation function in **pPb** is **unmodified** with respect to an **interpolated pp reference**

Jet Fragmentation Function in pPb

CMS-PAS-HIN-15-004

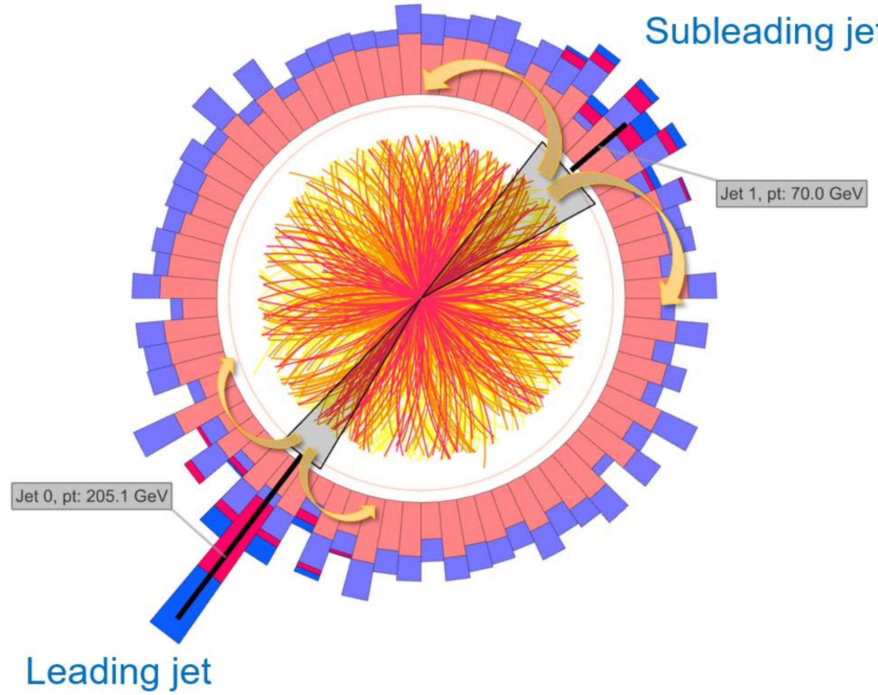




The observed modification in **PbPb** collisions is not coming from initial state effects

Jet fragmentation function in **pPb** is **unmodified** with respect to an **interpolated pp reference**

Recent CMS Results on Jet Quenching



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how transverse momentum is distributed inside the jet cone

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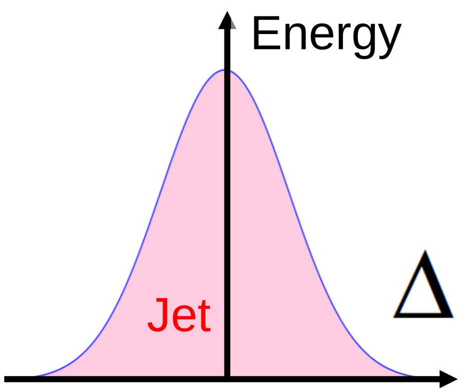
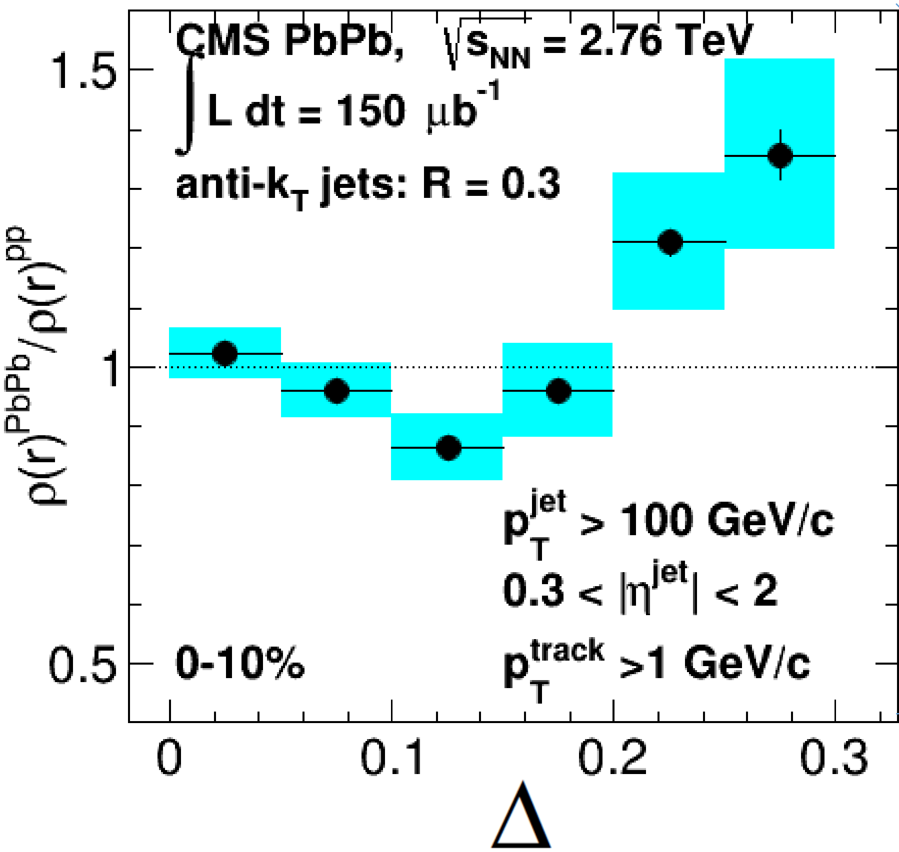


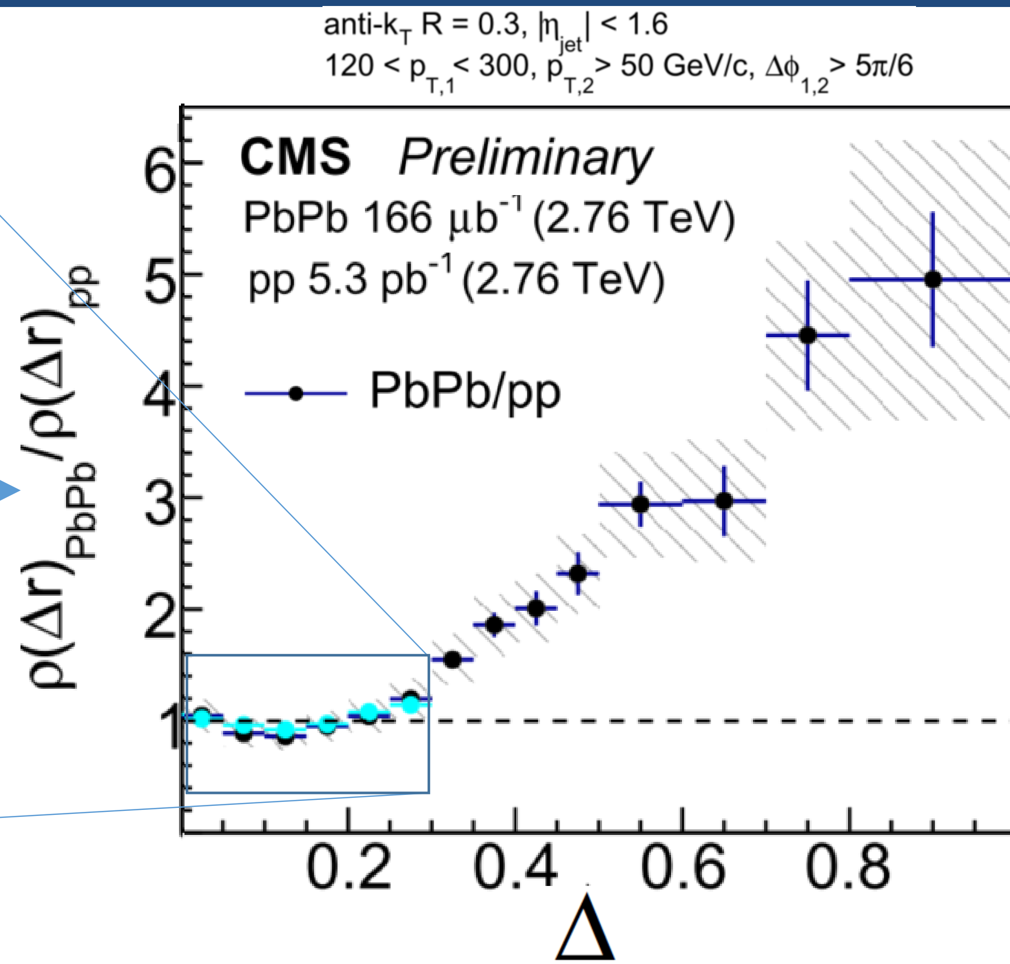
Quenched Energy Flow:
"angular distribution of the associated transverse momentum"

Flavor Dependence of the Parton Energy Loss
through heavy flavor meson suppression

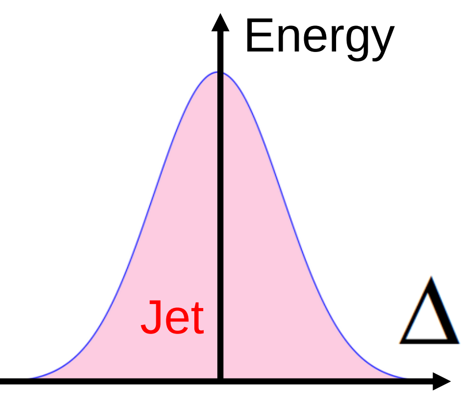
High p_T Jet Shape in PbPb @ 2.76 TeV

Jet shape **PbPb / pp**





$$\Delta = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

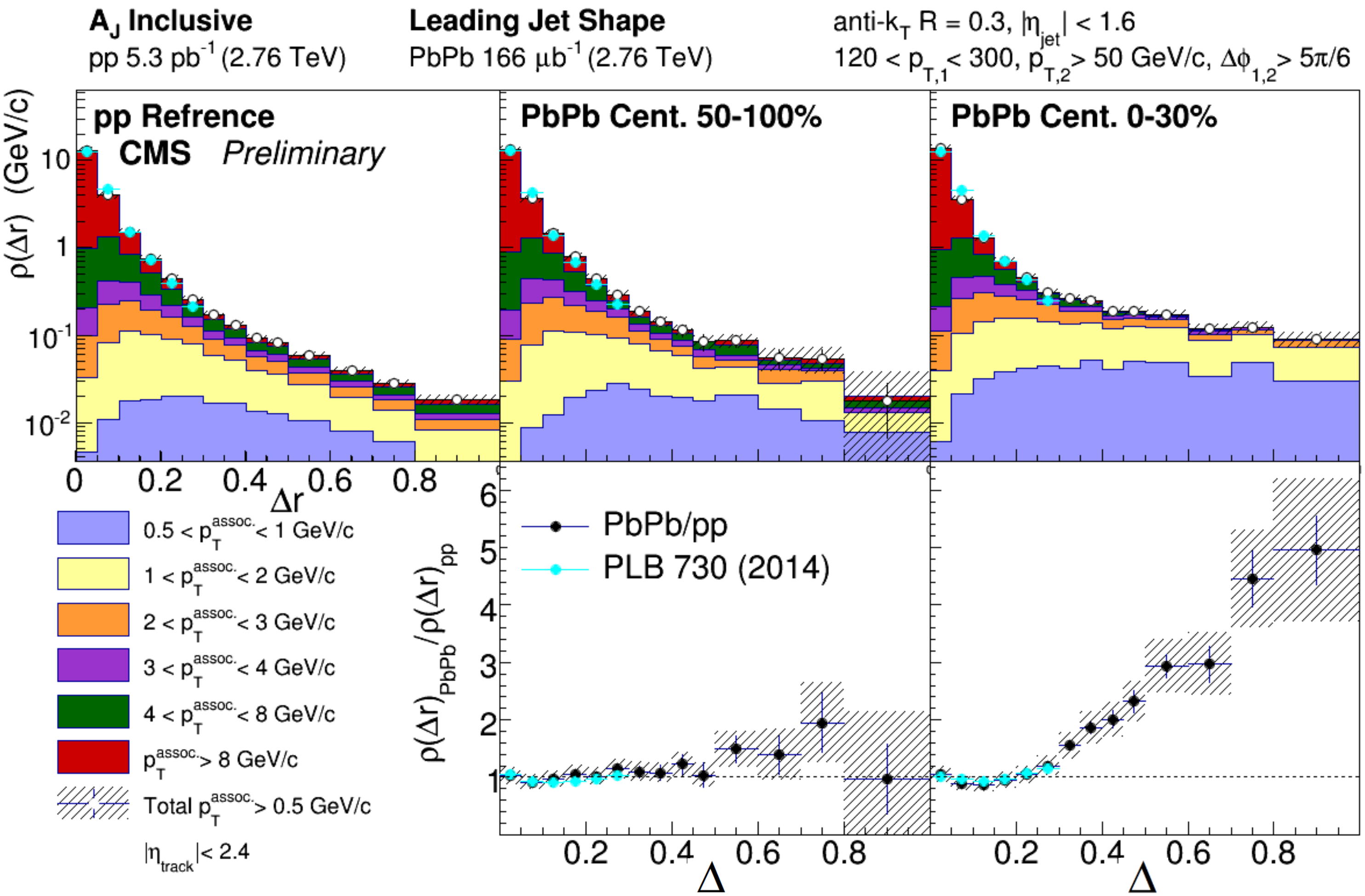


Observation of energy redistribution inside the jet cone

The bulk of the Jet structure at the core of the jet is actually pretty similar to that in pp

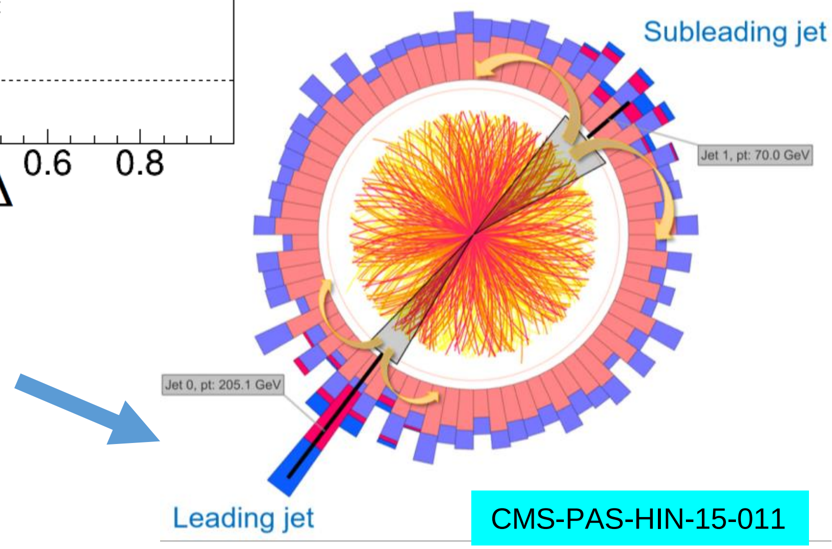
CMS-PAS-HIN-15-011

Leading Jet shapes in PbPb @ 2.76 TeV



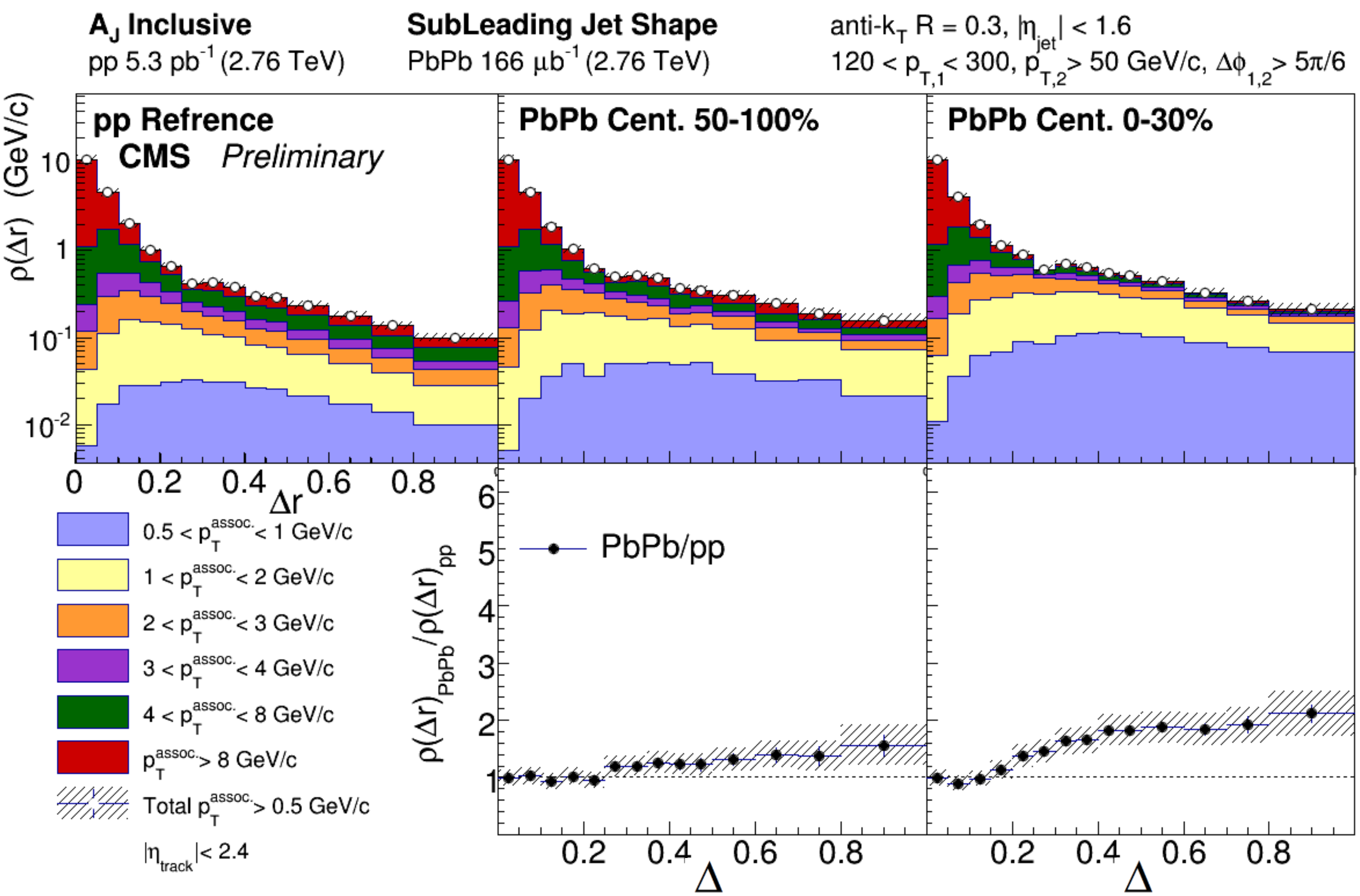
Obtained from a **two-particle correlation** method (jet-track) with mixed event background subtraction

- Small modification of the core of the jet (small Δ region, dominated by high p_T particles)
- Sizable modification in the tail part of the jet (large Δ region, dominated by low p_T particles)
- Leading jet shape modification is compared to the published inclusive jet shape



CMS-PAS-HIN-15-011

Subleading Jet shapes in PbPb @ 2.76 TeV



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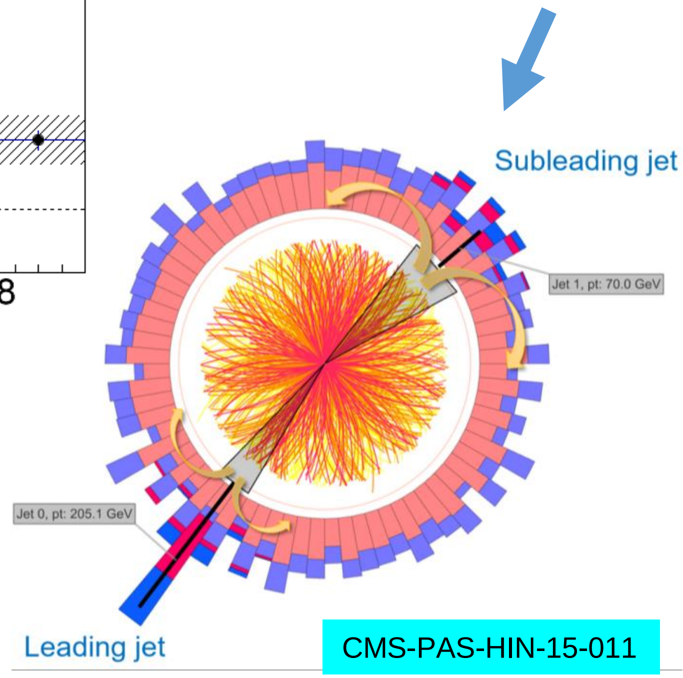
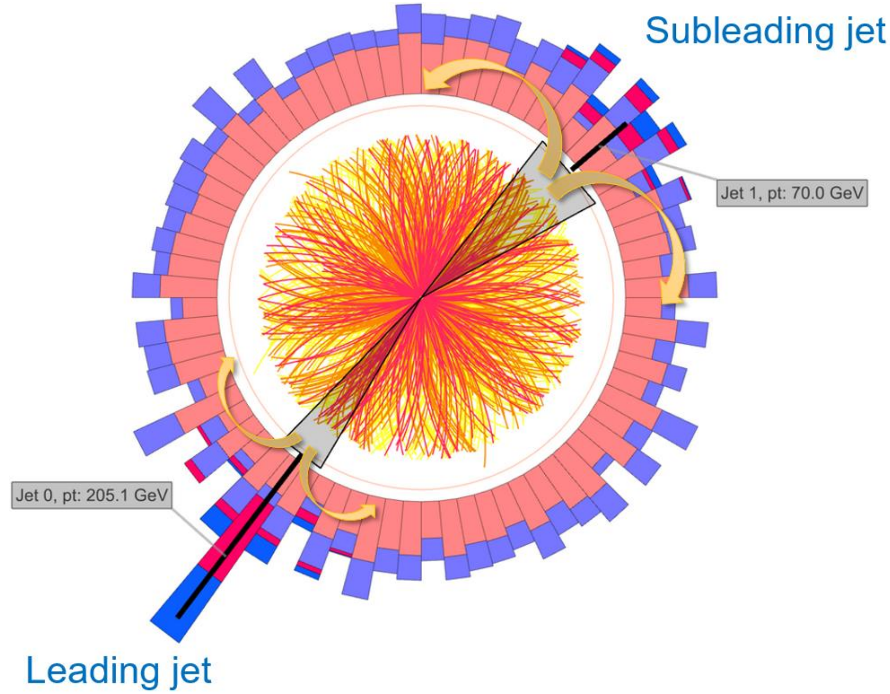


CMS-PAS-HIN-15-011

- Subleading jet shapes are wider than the leading jet shape
- Significant modification is observed in large Δ region (dominated by low pT particles)

Recent CMS Results on Jet Quenching

Jet Fragmentation Function:
how transverse momentum is distributed inside the jet cone



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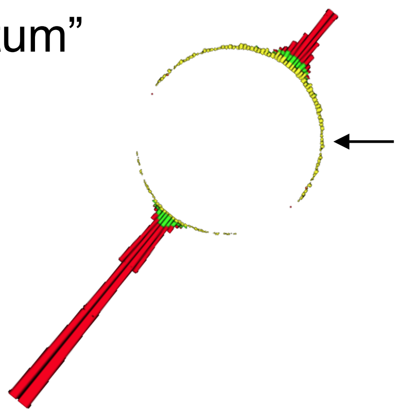
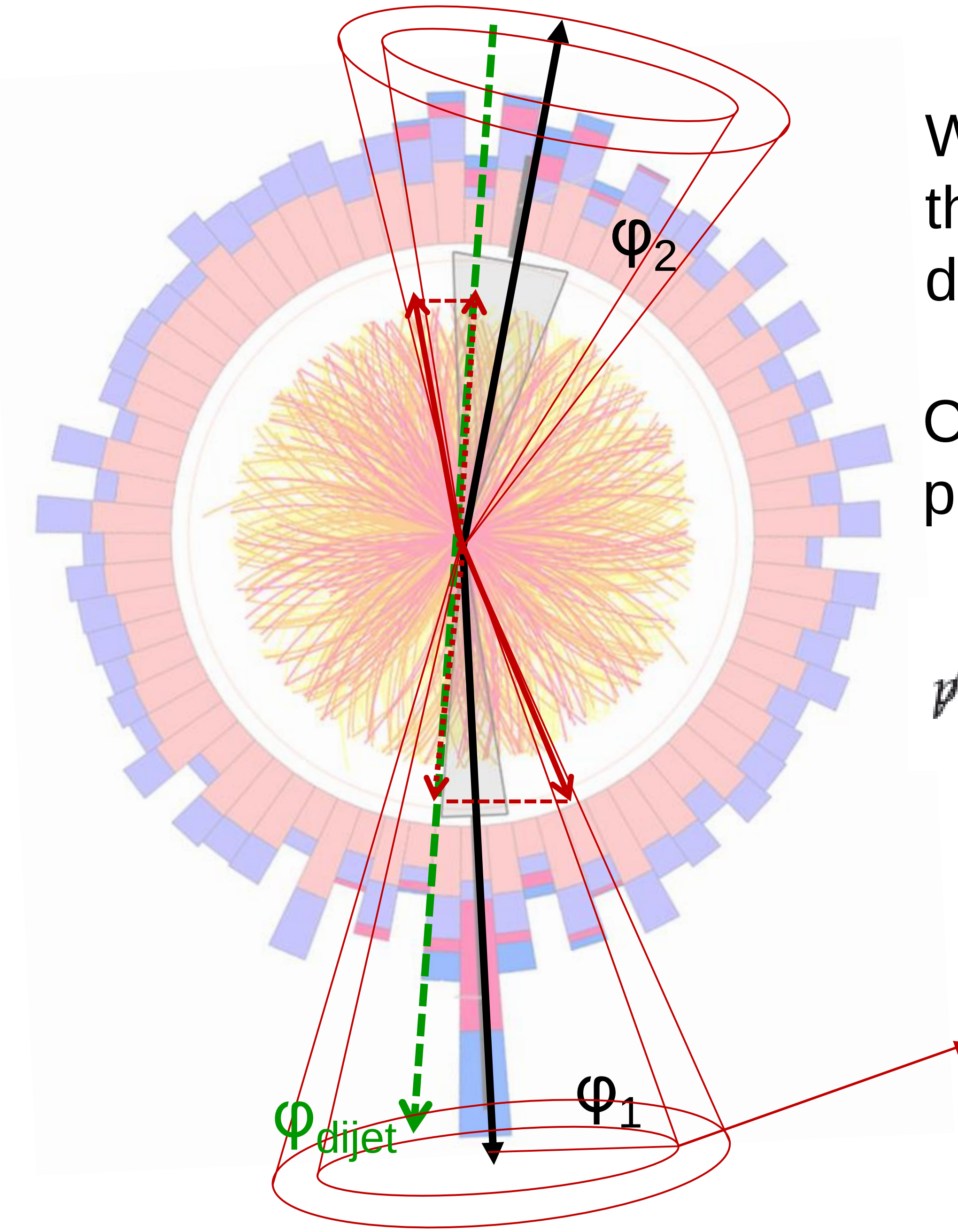


Flavor Dependence of the Parton Energy Loss
through heavy flavor meson suppression

Missing $p_T^{||}$ vs. Δ



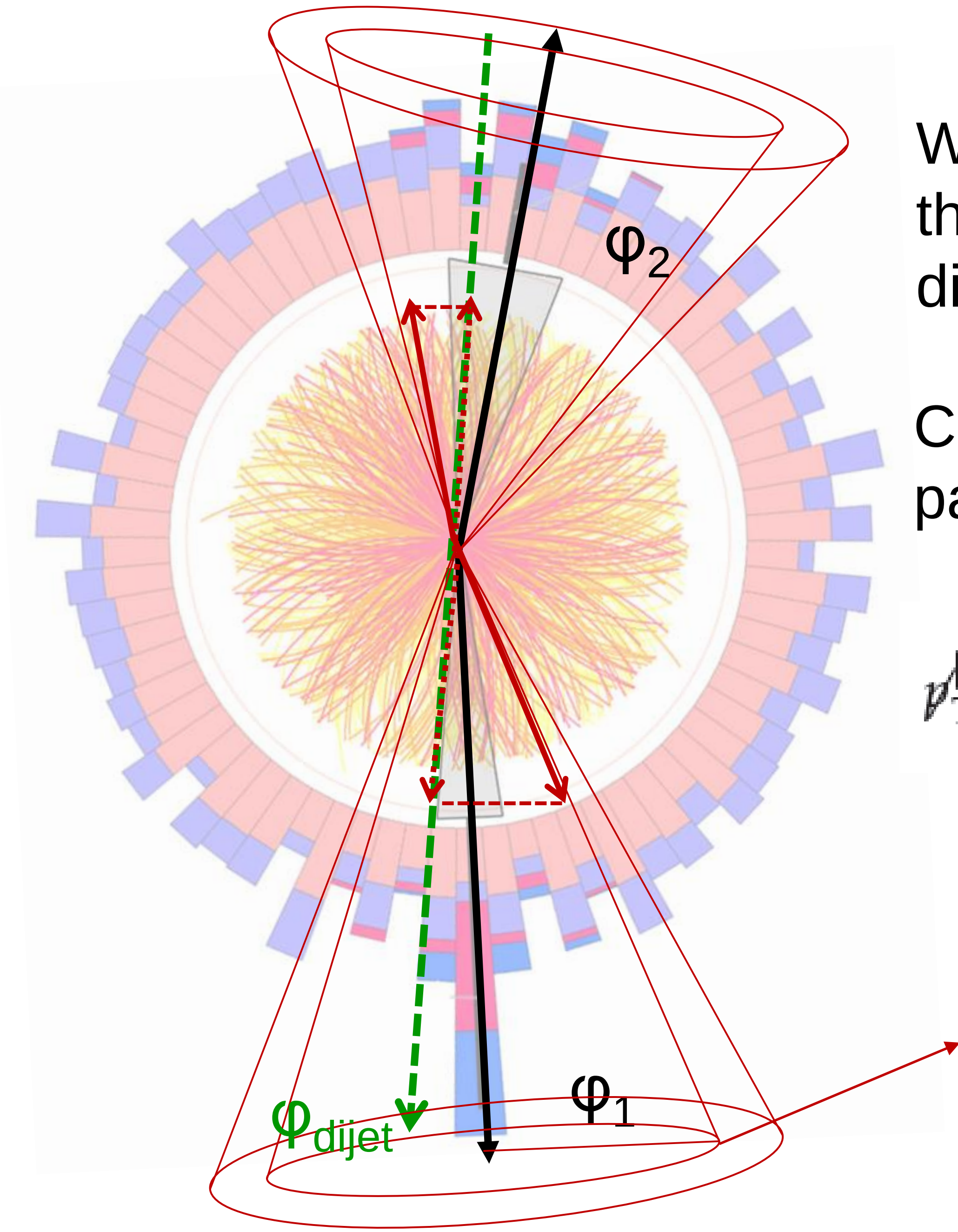
What is the angular distribution of these particles with respect to the dijet system?

Calculate the missing p_T for charged particles that fall in slices of Δ

$$\not{p}_T^{||} = \left(\sum_i -p_T^i \cos\left(\phi_i - \phi_{dijet}\right) \right) |_{R_{down} < \Delta < R_{up}}$$

$$\Delta = \sqrt{\Delta\phi^2_{Trk,jet} + \Delta\eta^2_{Trk,jet}}$$

Missing $p_T^{||}$ vs. Δ



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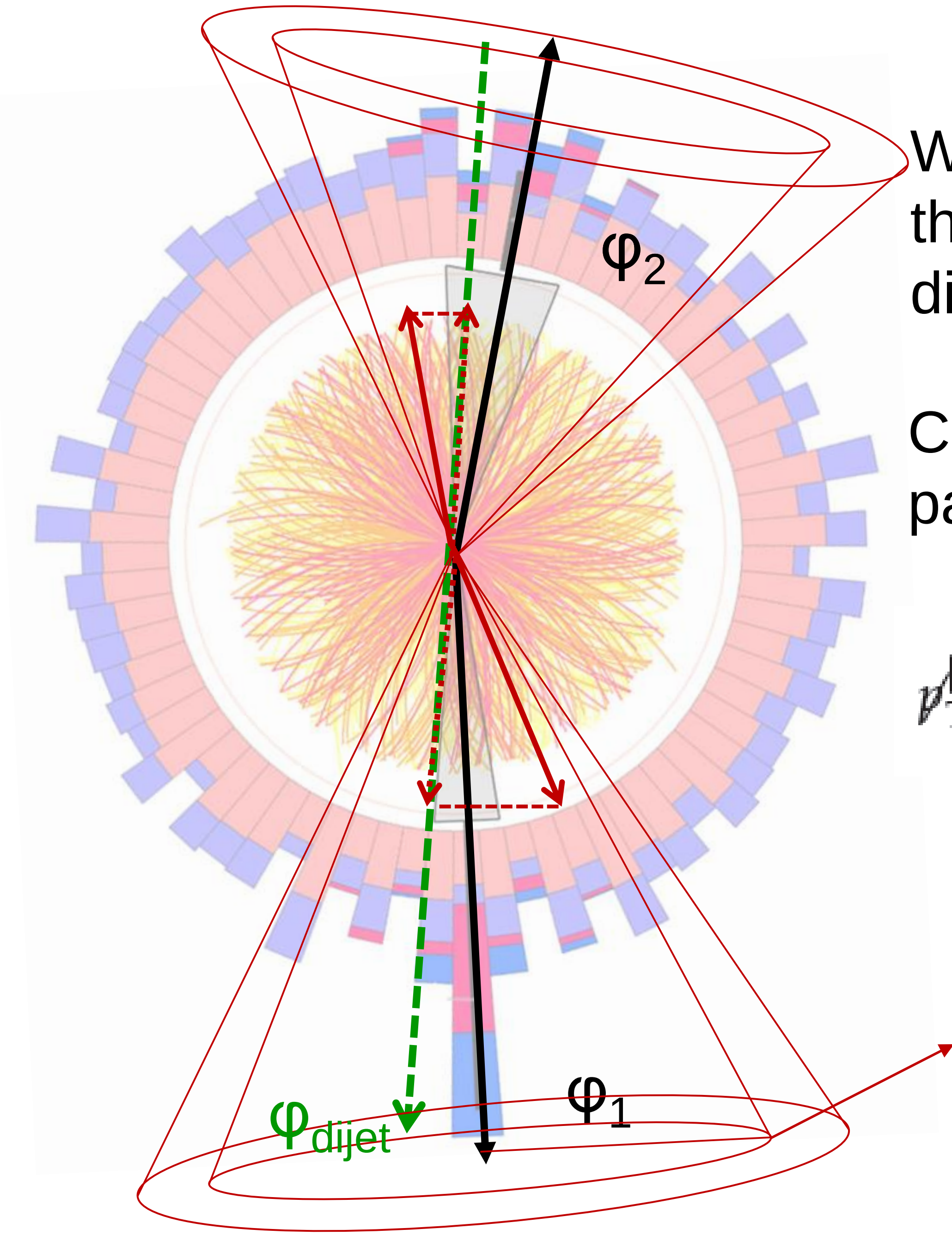

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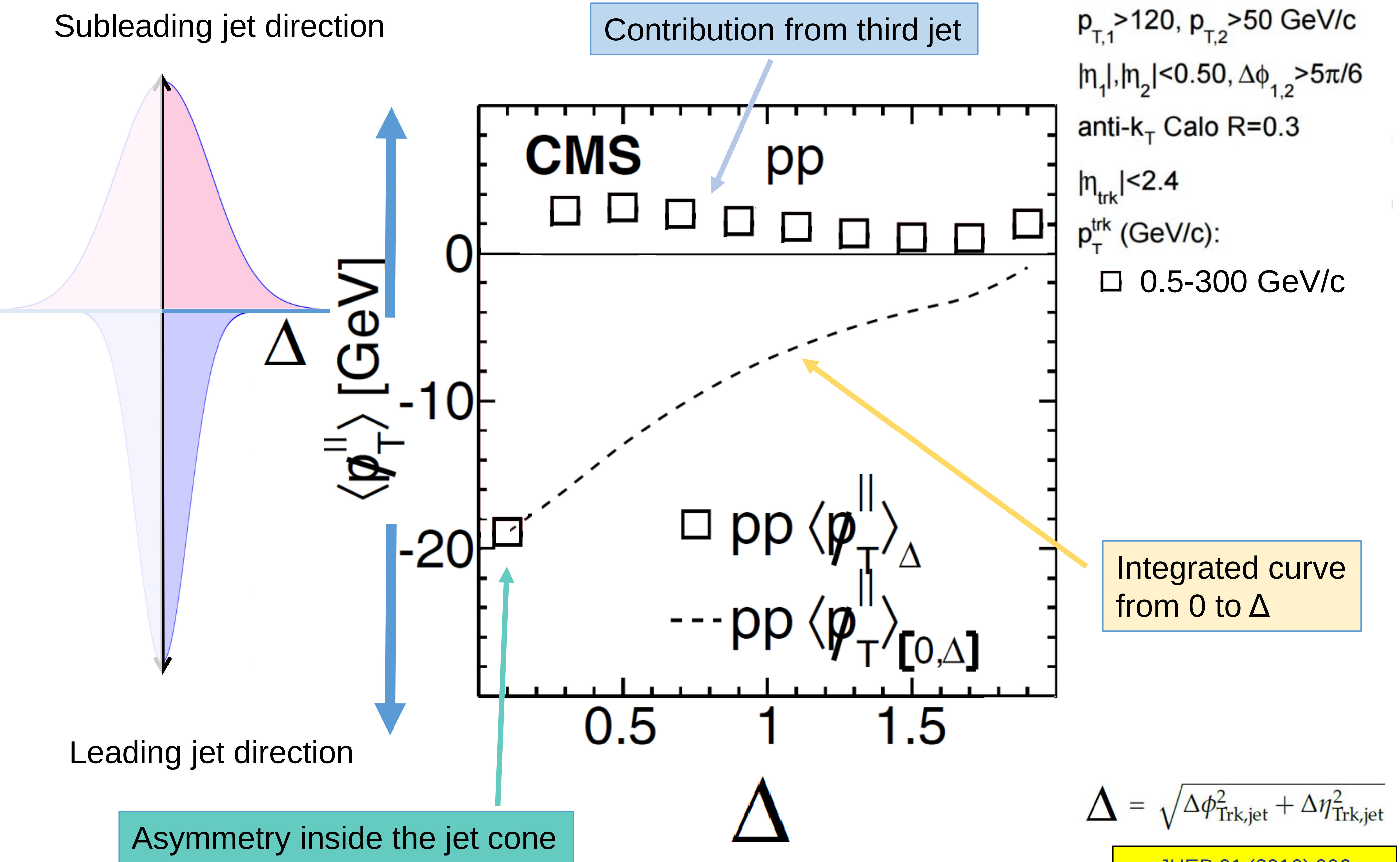
Missing $p_T^{||}$ vs. Δ in pp



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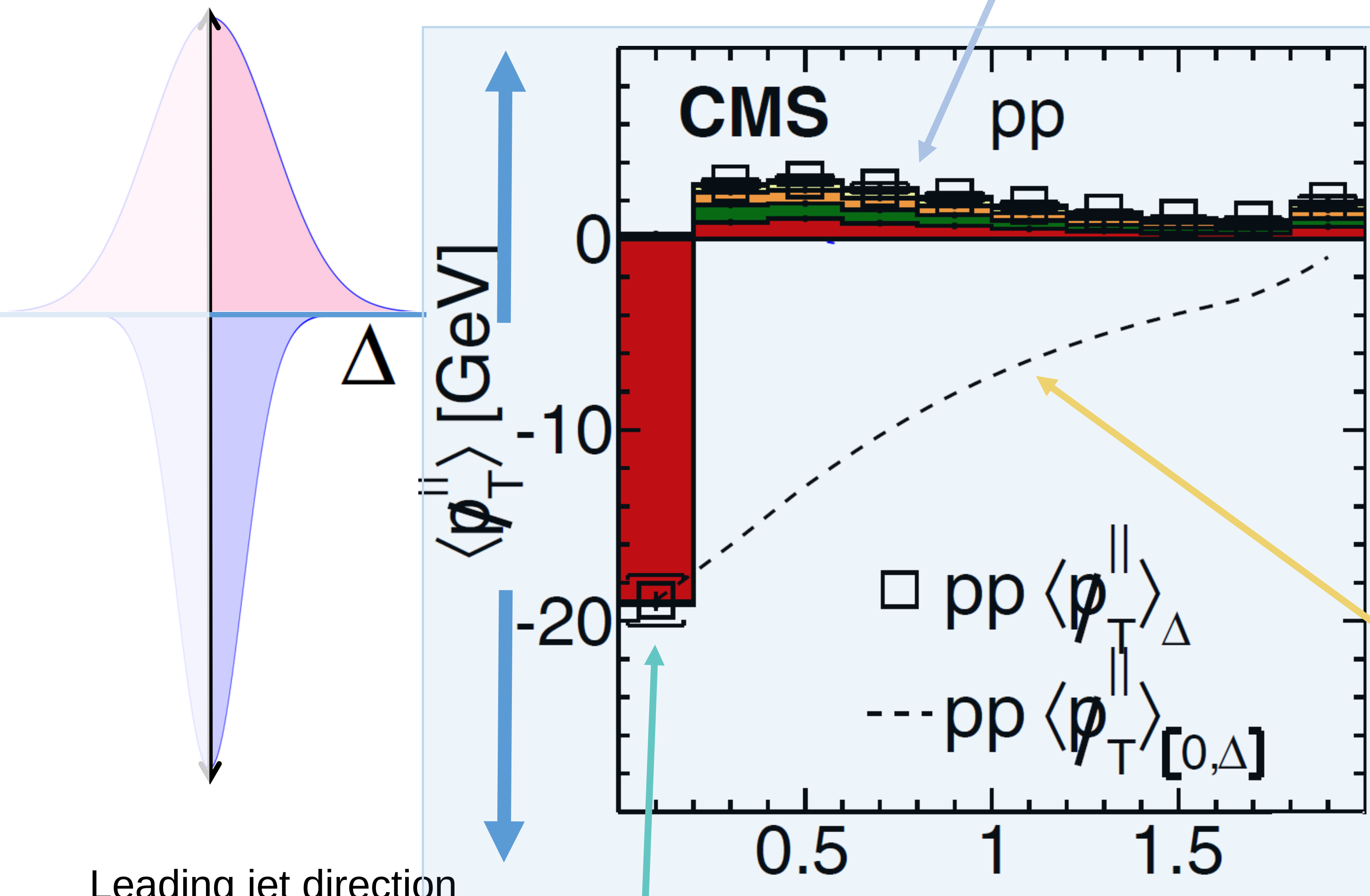
Missing $p_T^{||}$ vs. Δ in pp

Subleading jet direction

Contribution from third jet



Leading jet direction

$p_{T,1}>120$, $p_{T,2}>50$ GeV/c

$|\eta_1|,|\eta_2|<0.50$, $\Delta\phi_{1,2}>5\pi/6$

anti-k_T Calo R=0.3

$|\eta_{trk}|<2.4$

p_T^{trk} (GeV/c):

0.5 - 1.0 | 2.0 - 4.0

1.0 - 2.0 | 4.0 - 8.0

□ >0.5 | 8.0 - 300.0

Integrated curve from 0 to Δ

Asymmetry inside the jet cone

Δ

$$\Delta = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

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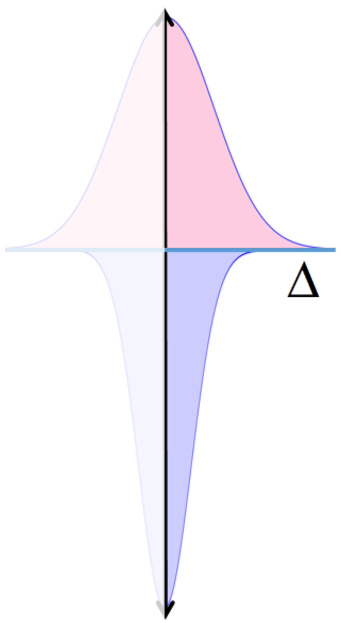
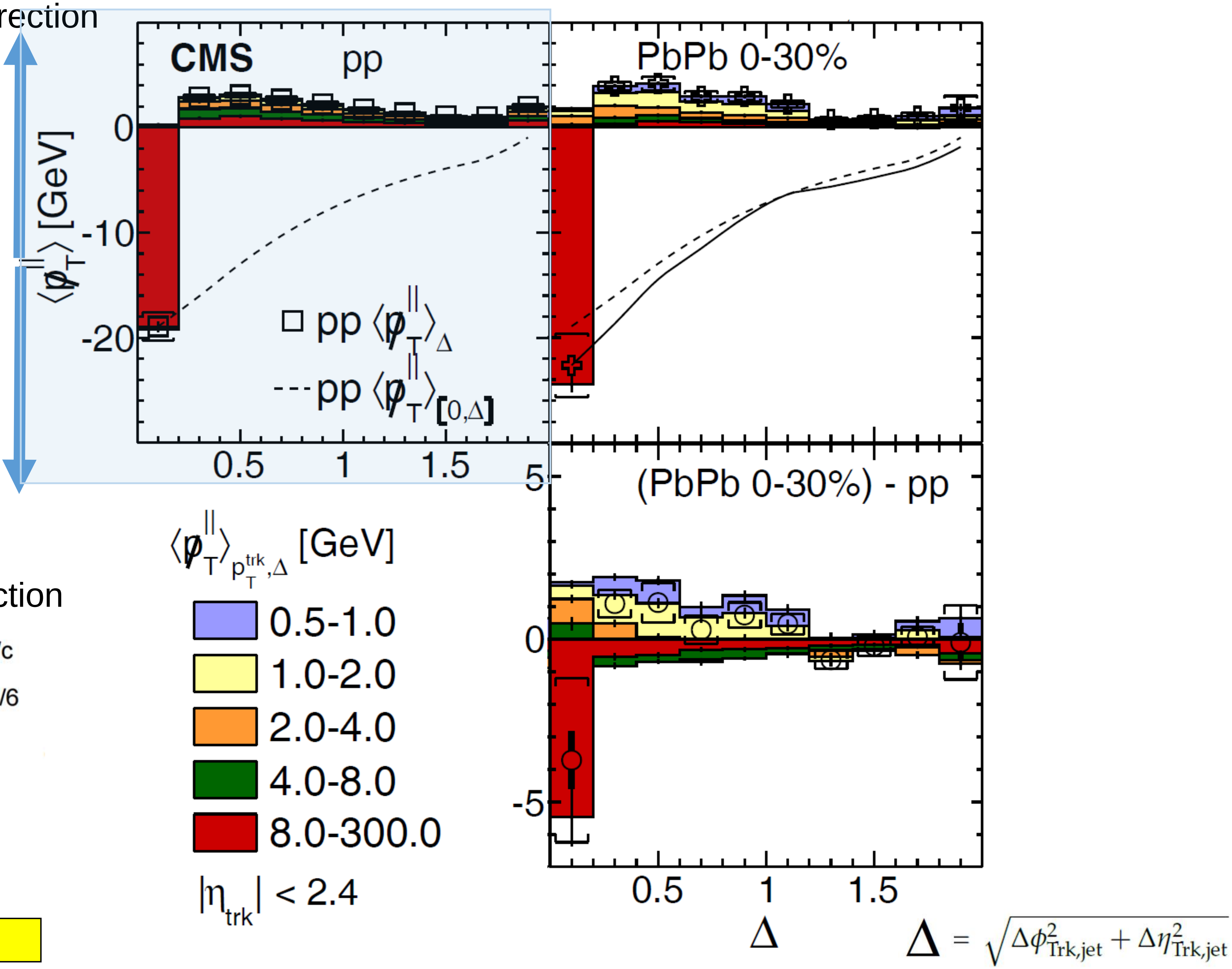
Missing $p_T^{||}$ vs. Δ





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Inclusive A_J

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Missing $p_T^{||}$ vs. Δ

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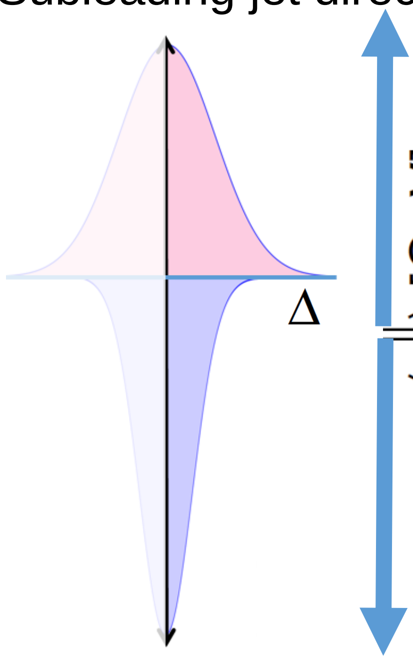

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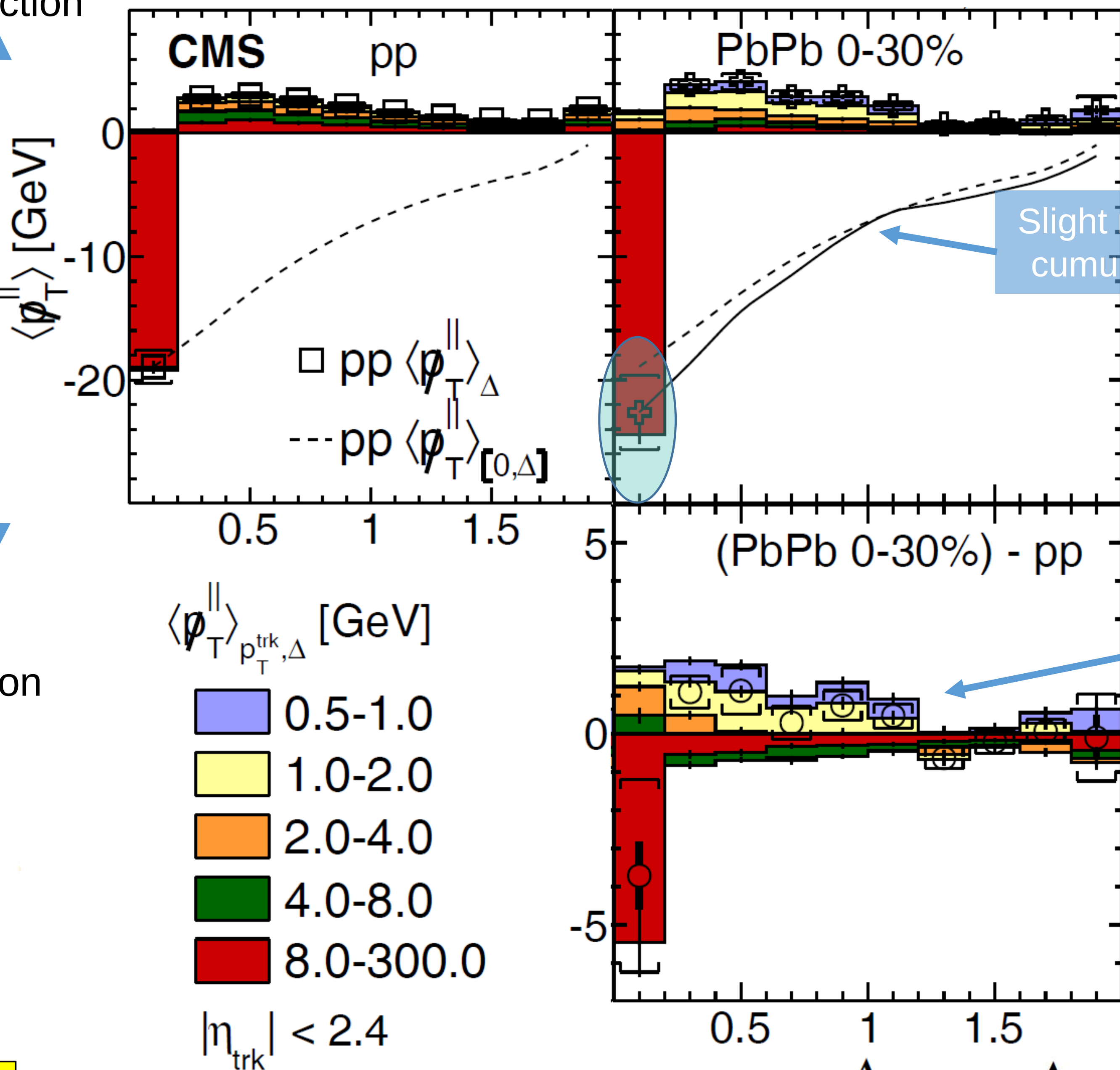

Slight modification of the cumulative energy flow

Open circles: Integrated over particle p_T

$$\Delta = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

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Missing $p_T^{||}$ vs. Δ

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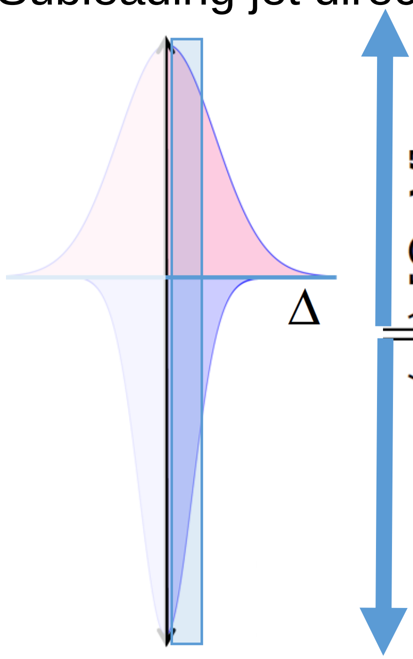

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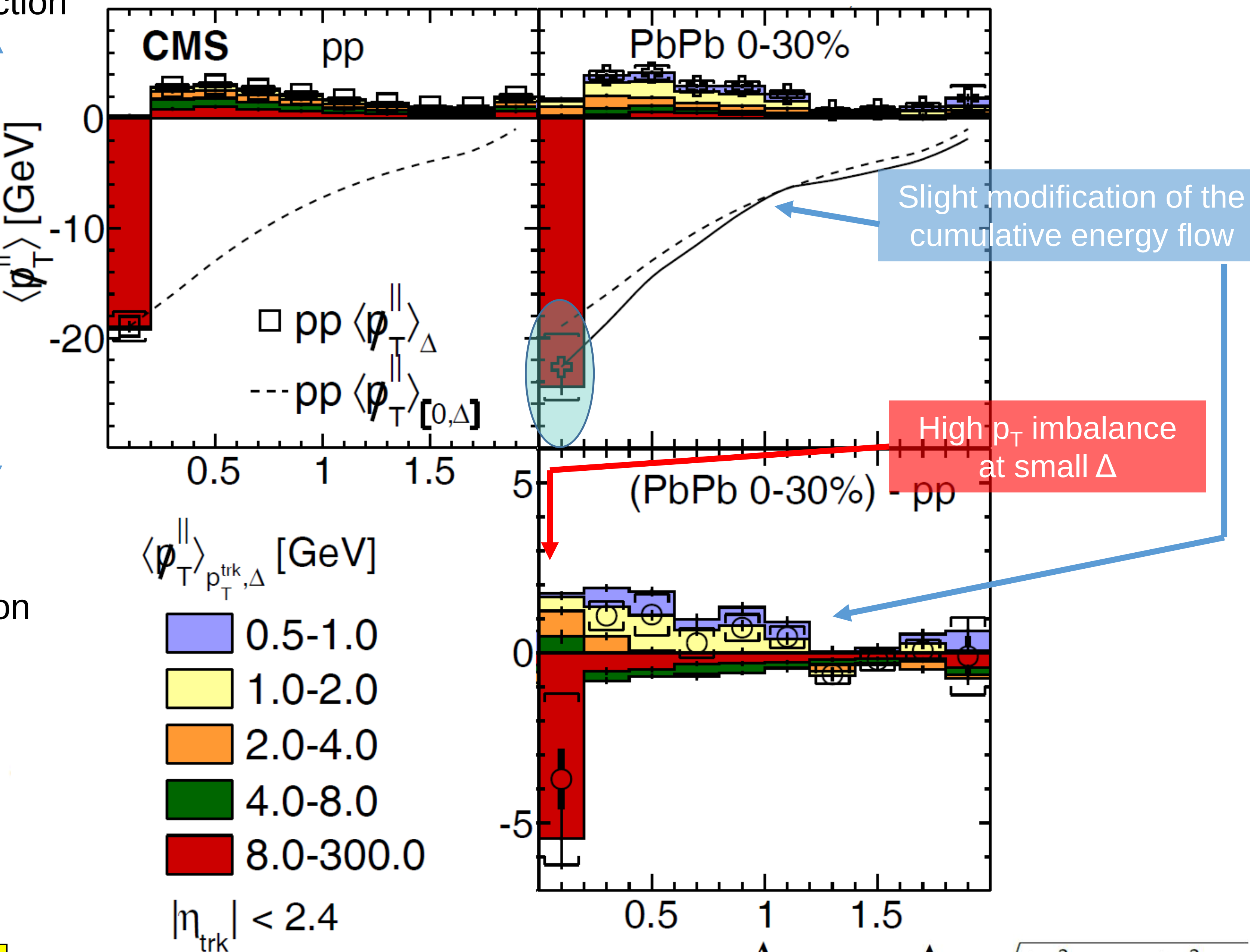

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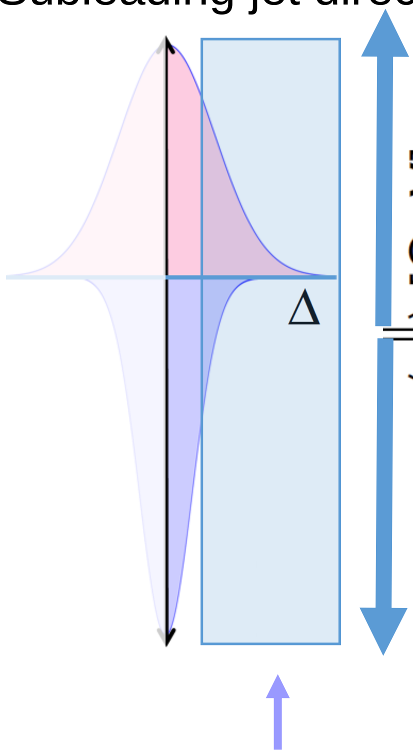

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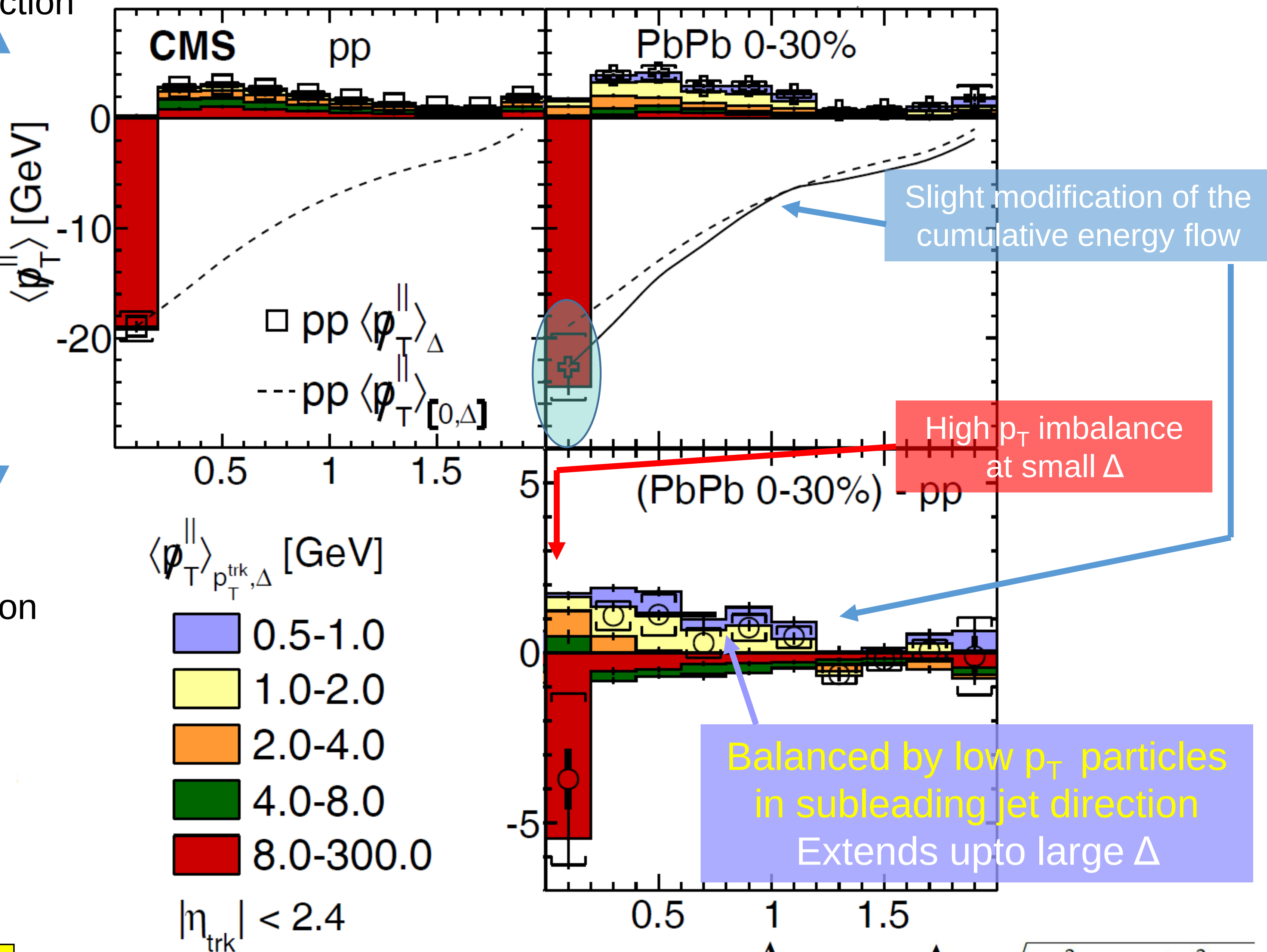

$$\Delta = \sqrt{\Delta\phi^2_{\rm Trk,jet} + \Delta\eta^2_{\rm Trk,jet}}$$

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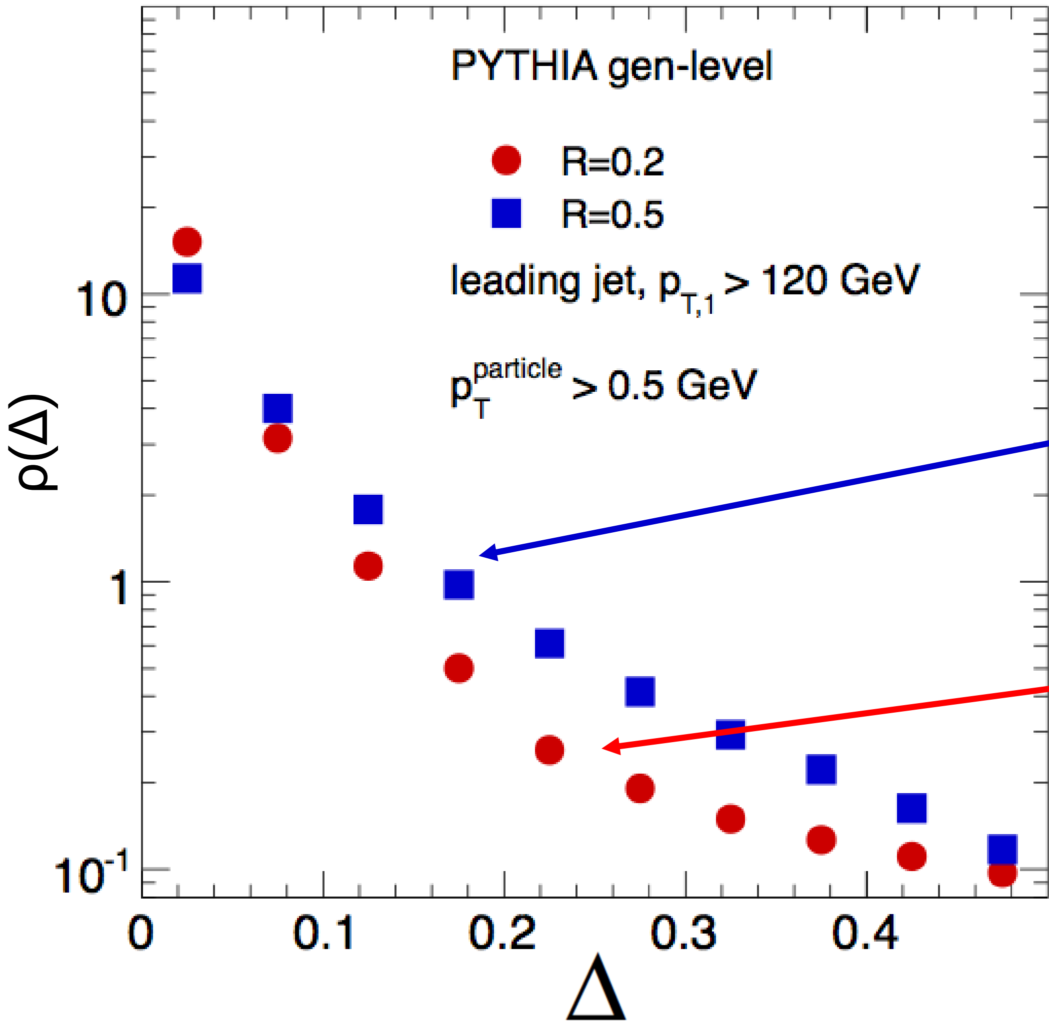
Anti-k_T Jets with Different R Parameters



Jet shape from PYTHIA

Jets reconstructed with R=0.5 gives ”**wider**” jet

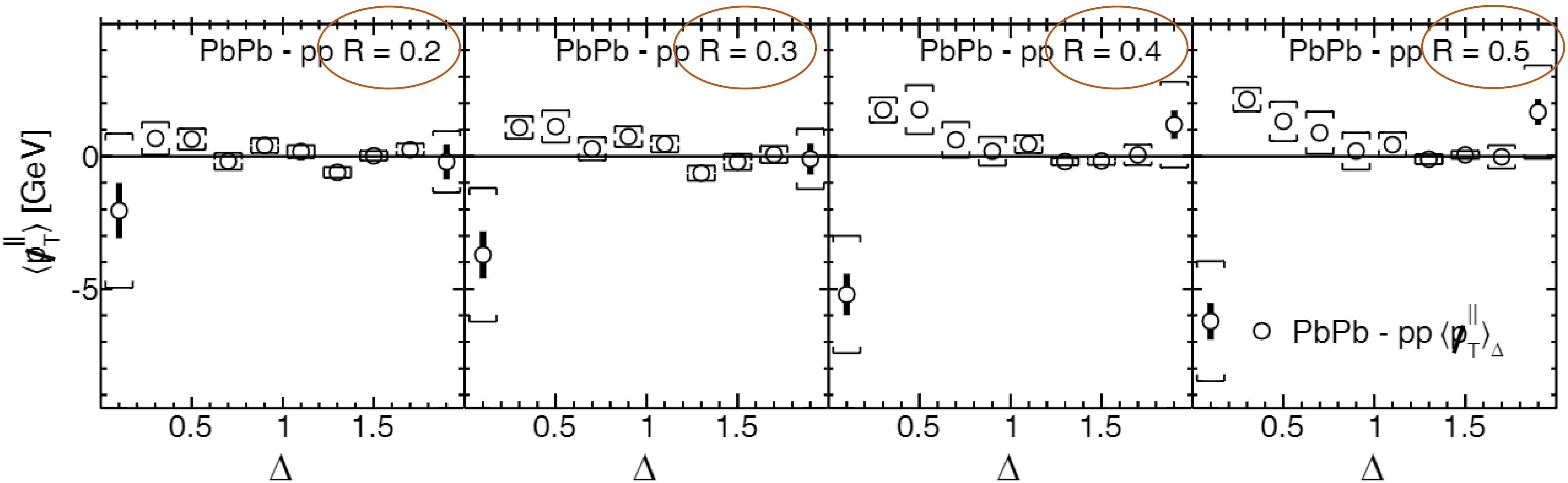
Jets reconstructed with R=0.2 gives ”**narrower**” jet

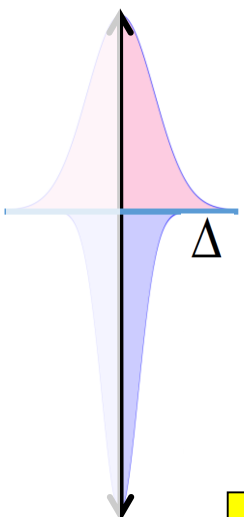
- Jets are only meaningful if the algorithm is defined
- Different parameter R select **different sets of dijet events!!**
- **Jet width dependent studies**

"Shooting Jets with Different Width" through the Medium

Narrower jets

Wider jets





- Quenched energy distribution depends on the R parameter used in the Anti-k_T algorithm

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$$\Delta = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

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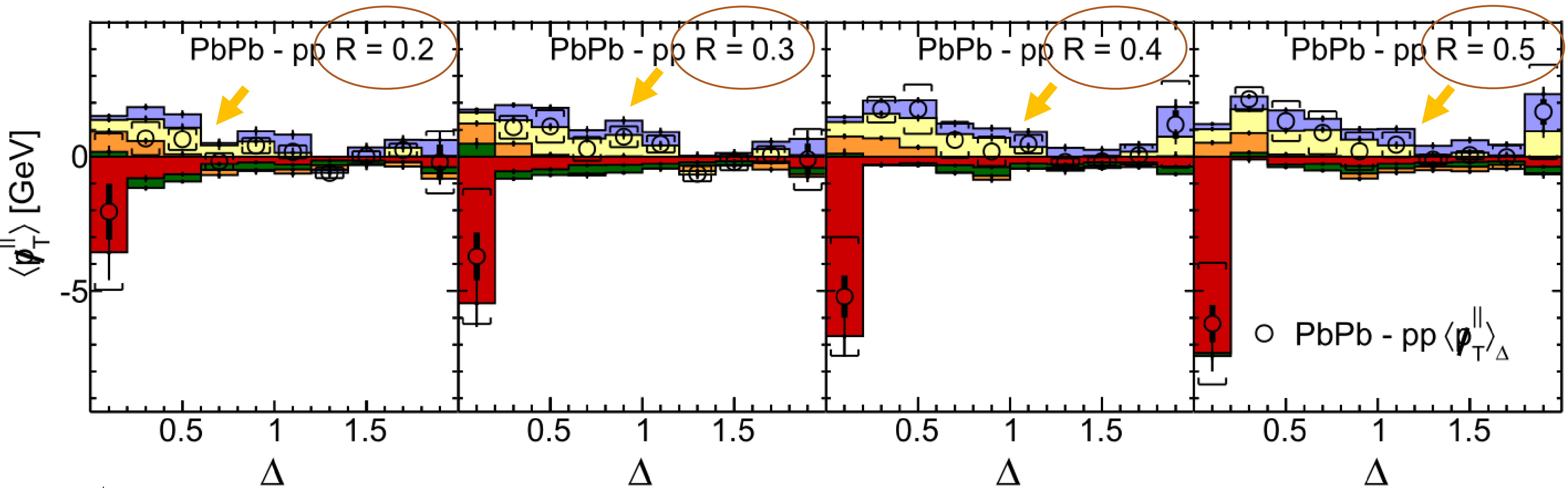
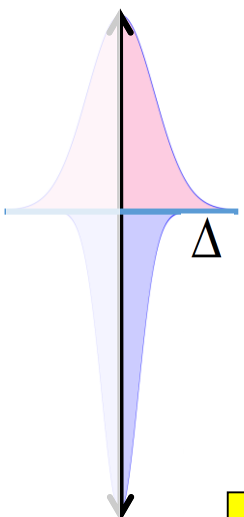
Narrower jets

Wider jets





- Quenched energy distribution depends on the R parameter used in the Anti-k_T algorithm
- Soft particles extends to larger Δ in dijet events reconstructed with larger R parameter

p_T^{trk} (GeV/c):

- 0.5 - 1.0
- 1.0 - 2.0
- >0.5
- 2.0 - 4.0
- 4.0 - 8.0
- 8.0 - 300

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$$\Delta = \sqrt{\Delta\phi^2_{\mathrm{Trk,jet}} + \Delta\eta^2_{\mathrm{Trk,jet}}}$$

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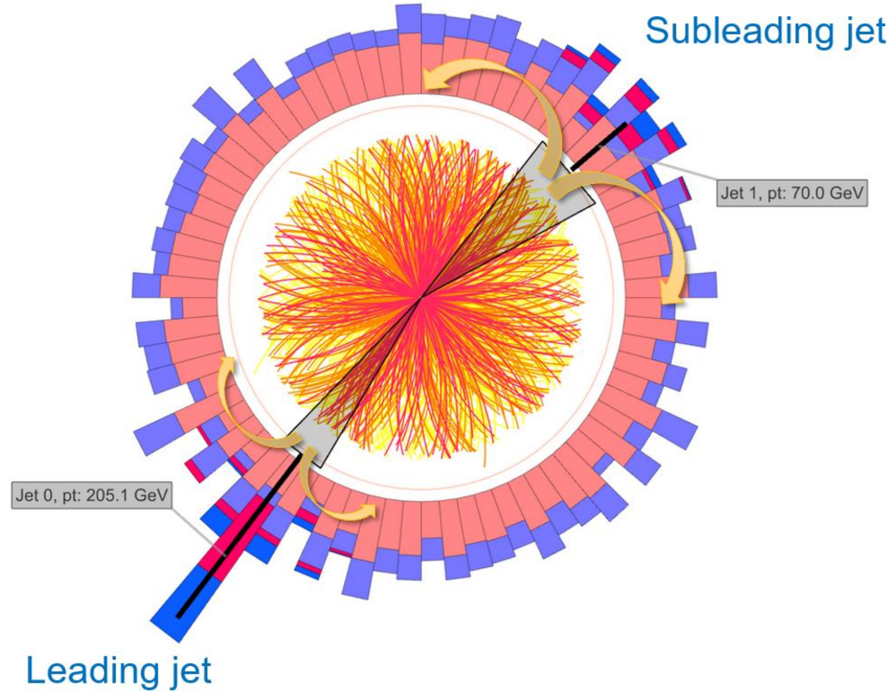


Jet Shape: "the jet energy distribution" as a function of Δ

Quenched Energy Flow: "angular distribution of the associated transverse momentum"

Flavor Dependence of the Parton Energy Loss

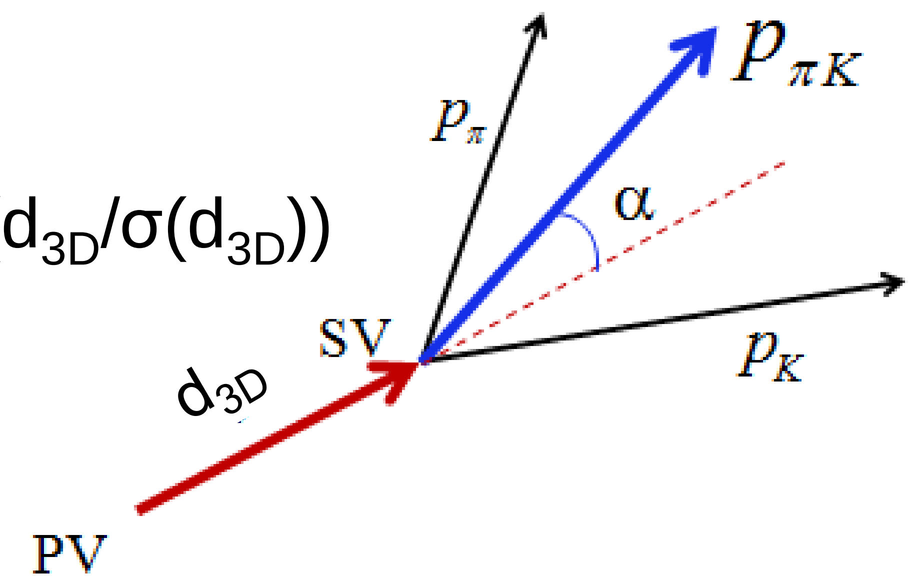
through heavy flavor meson suppression

D^0 Reconstruction in PbPb

- **$D^0 \rightarrow K^- \pi^+$, BR = 3.88±0.05%, $c\tau(D^0)$ = 122.9 μm**

- **D^0 candidates reconstructed by combining oppositely charged tracks**
  - Tracks with high purity selection, $|\eta|<1.1$ and $p_T > 1$ GeV/c
  - No (K-π) particle identification applied: two mass assignments for one track pair→**Two candidates for one track pair**

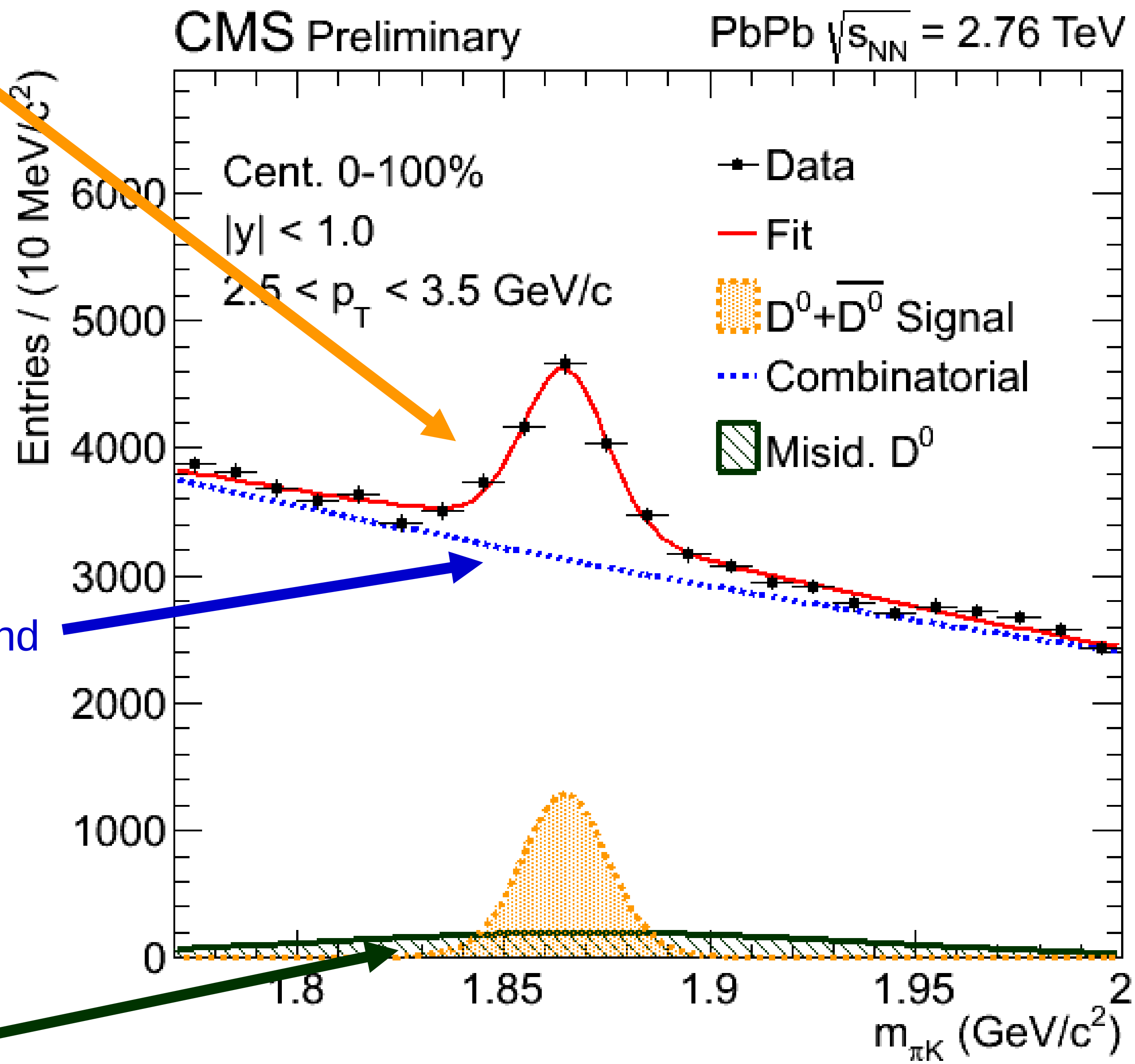
- **Topological selections:**
  - 3D decay length significance ($d_{3D}/\sigma(d_{3D})$)
  - Pointing angle α
  - Vertex χ^2 fit probability



D^0 Signal Extraction: $D^0 \to K^- \pi^+$

$D^0 \to K^- \pi^+$ signal (Double Gaussian)

Combinatorial background (Exponential function)



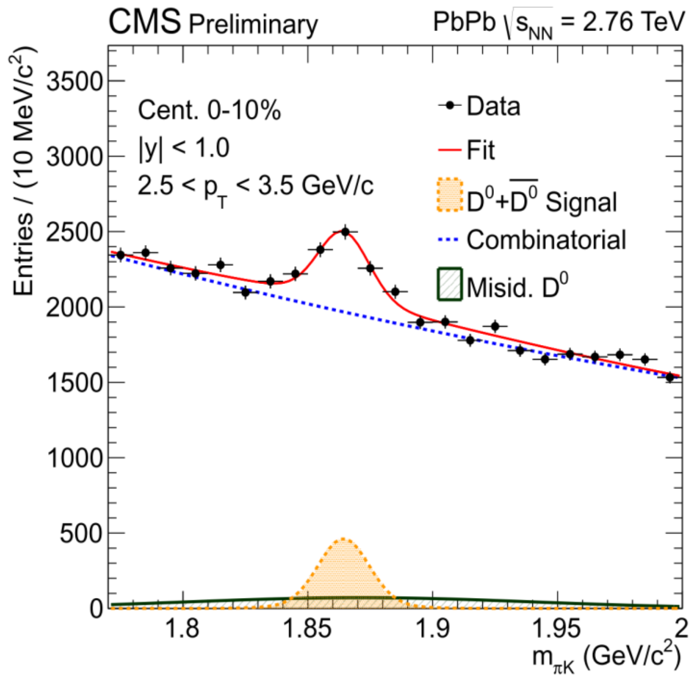
Misidentification (K-π swapped) due to wrong mass assignment (Gaussian)

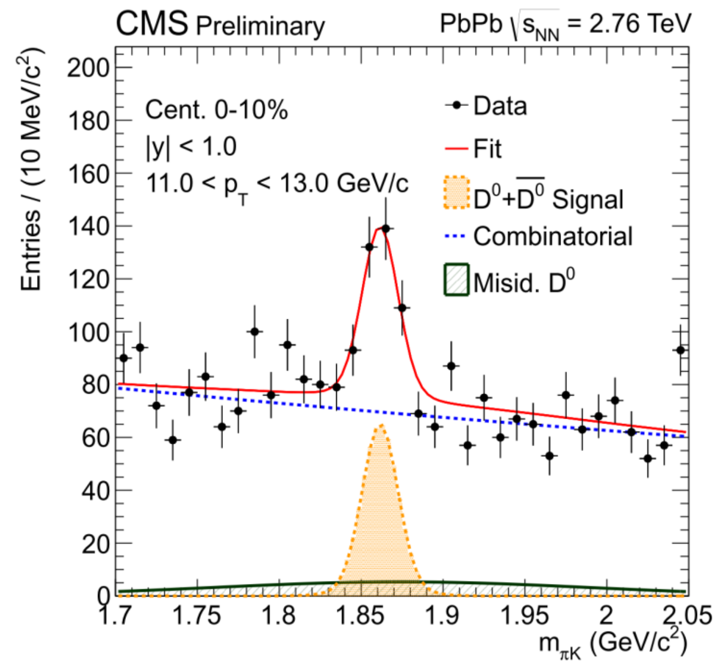
CMS PAS HIN-15-005

D^0 Signal to Background Ratio Comparison

0-10%

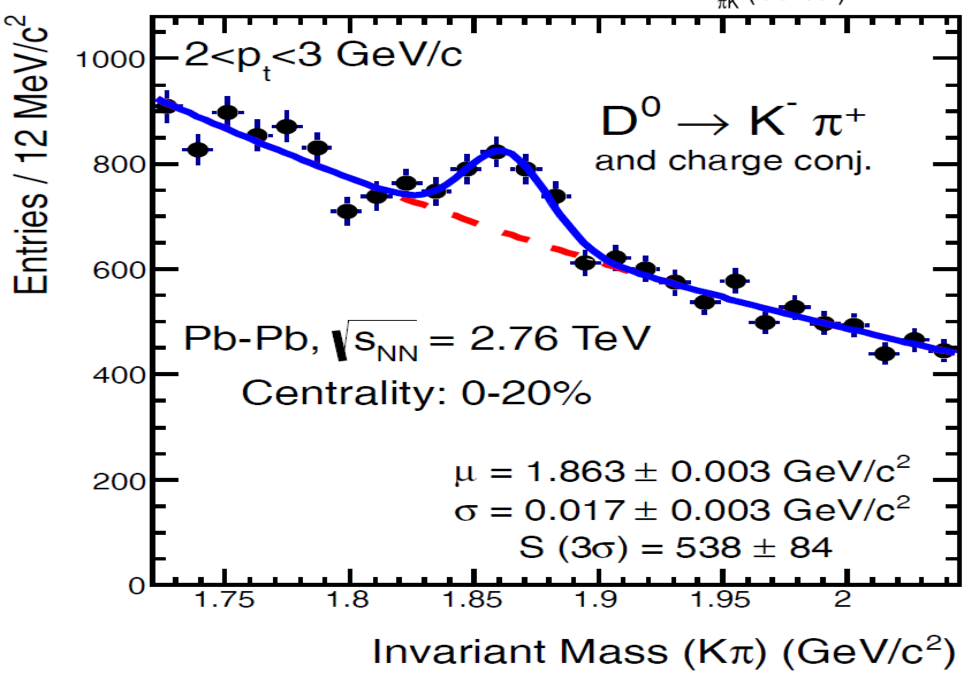
(No K-π ID)

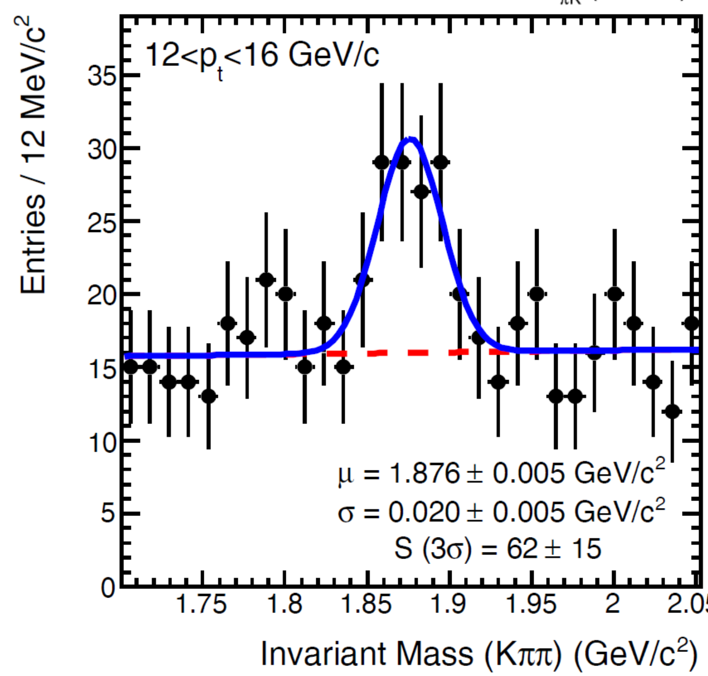




0-20%

ArXiv 1203.2160





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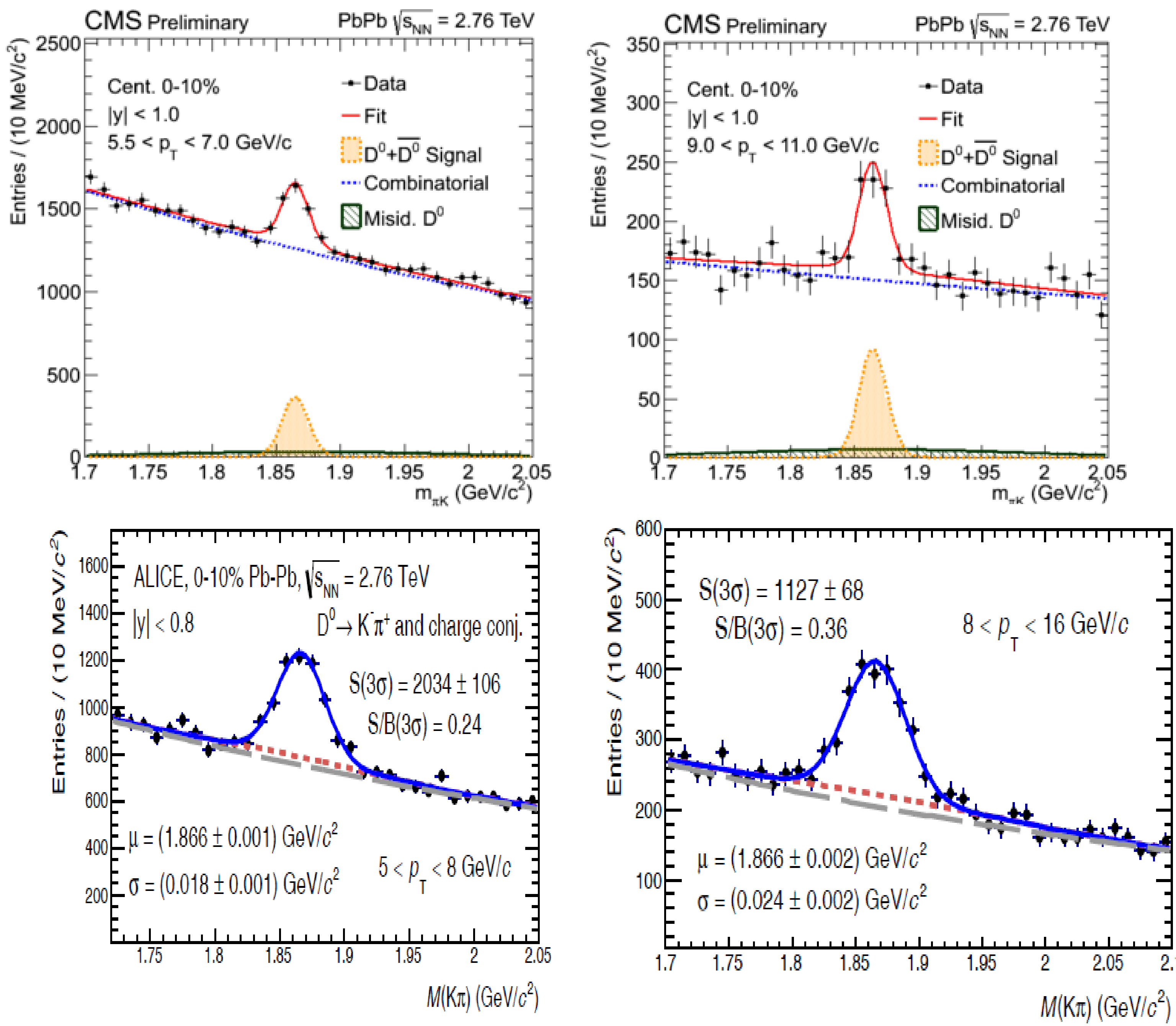
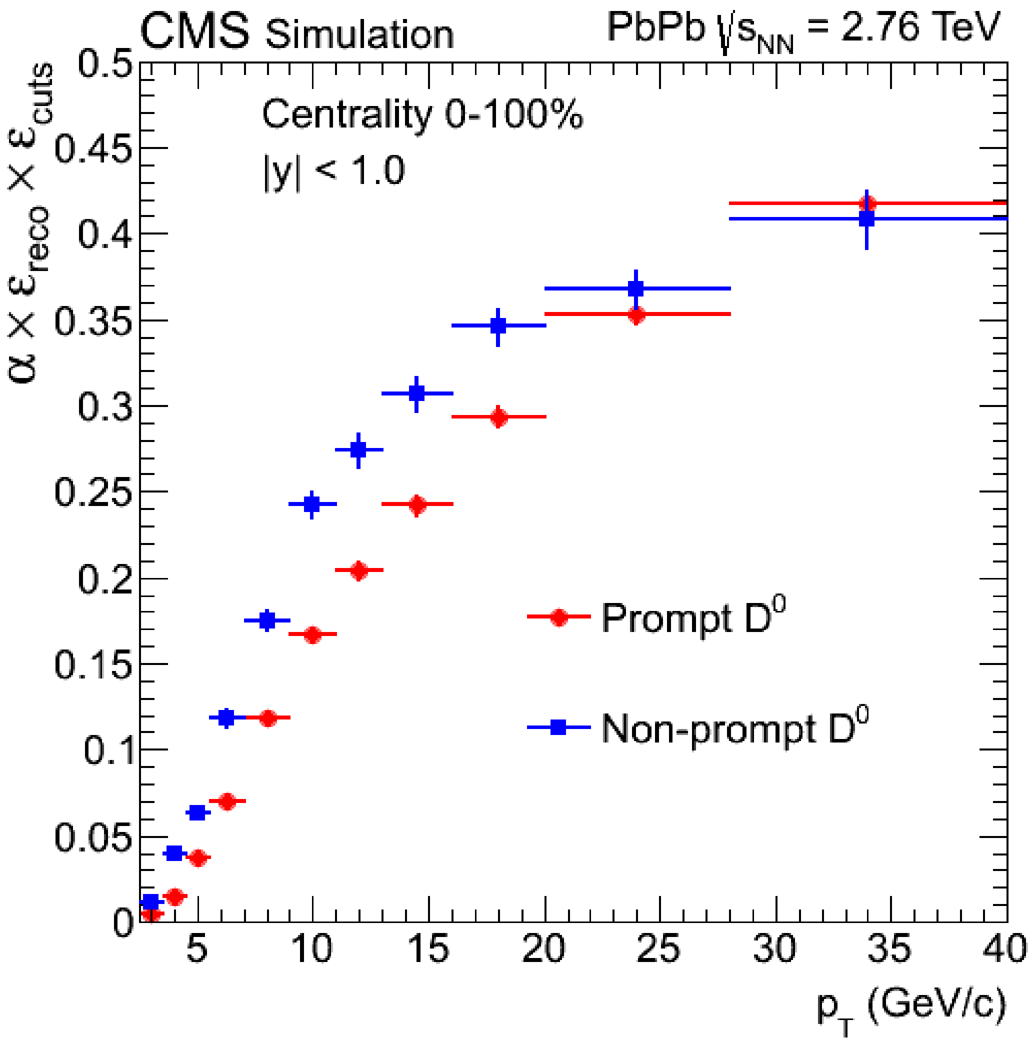


0-10%

ArXiv 1506.06604

Acceptance and Efficiency Correction

$$\frac{dN_{PbPb}}{dp_T} = \frac{f_{prompt} \cdot \frac{1}{2} N^{raw}_{D^0}}{\Delta p_T} \cdot \frac{1}{N_{MB} \cdot Br \cdot (\alpha \times \varepsilon)_{prompt}}$$



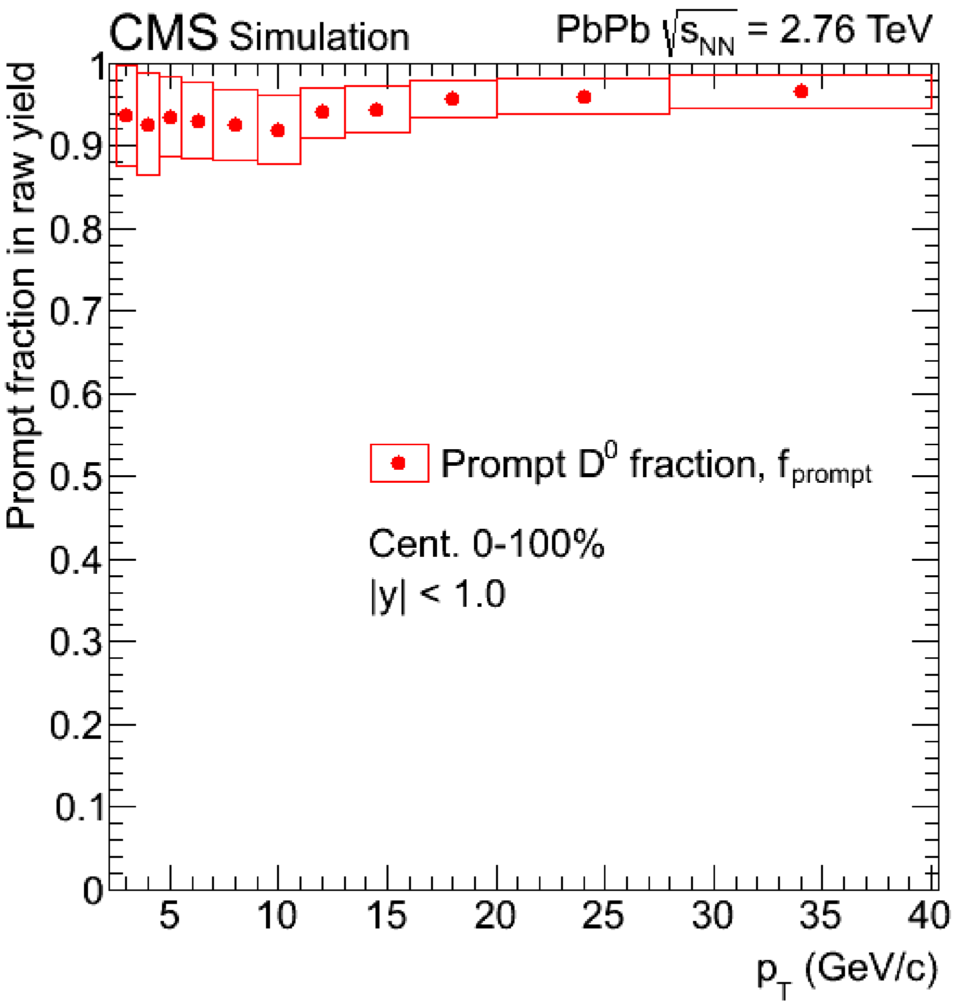
- Combined effects of tracking efficiency and D^0 meson selection efficiency

- Acceptance and efficiency of non-prompt D^0
  (D^0 from b-hadron decay)
  will be used to estimate the the B feed-down correction factor

CMS PAS HIN-15-005

B→D Feed-down Correction

$$\frac{dN_{PbPb}}{dp_T} = \frac{f_{prompt} \cdot \frac{1}{2} N^{raw}_{D^0}}{\Delta p_T} \cdot \frac{1}{N_{MB} \cdot Br \cdot (\alpha \times \varepsilon)_{prompt}}$$



CMS PAS HIN-15-005 | CMS PAS HIN-12-014

- Non-prompt D^0 subtraction:

$$f_{prompt} = 1 - \frac{N^{raw}_{Non-prompt\ D^0}}{\frac{1}{2} N^{raw}_{D^0}}$$

- Raw yield of non-prompt D^0
  - Beauty production from FONLL [1], decay with EvtGen or PYTHIA
  - Acceptance and efficiency from PYTHIA+HYDJET
  - R_{AA} of non-prompt D^0 constrained by non-prompt J/ψ and b-jet R_{AA}

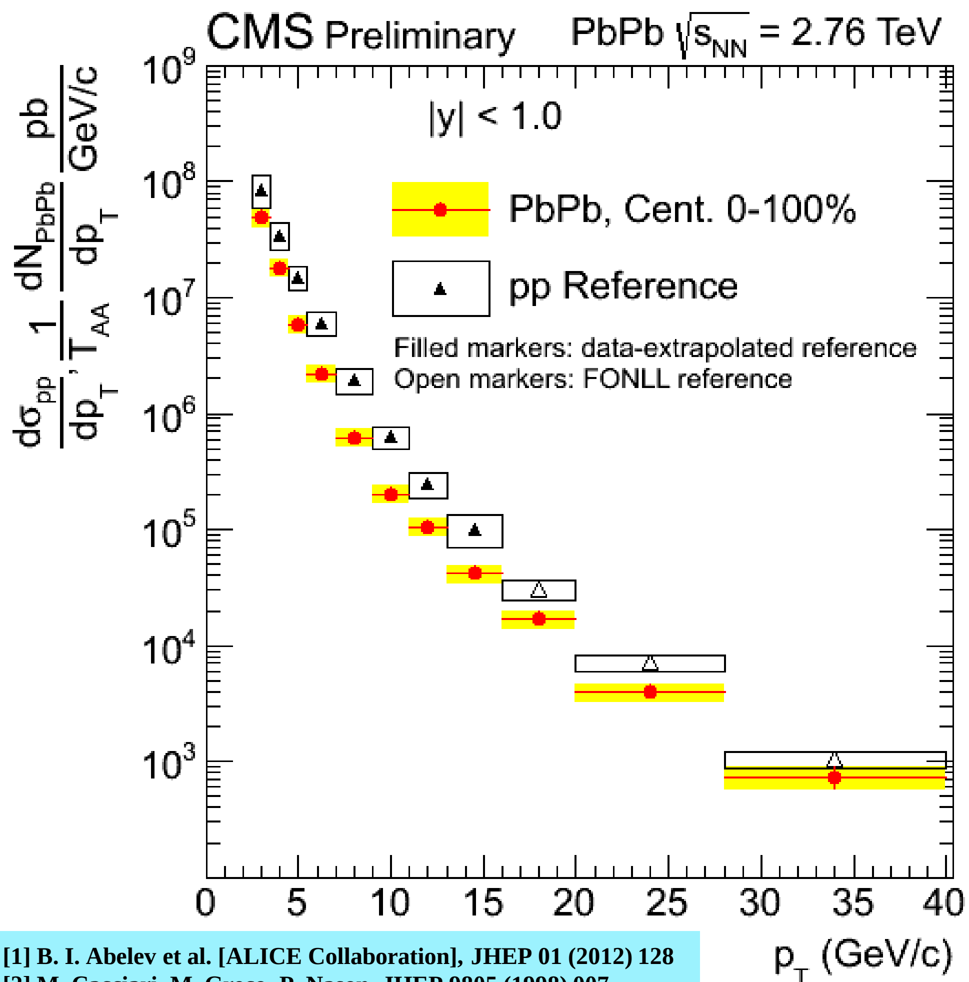
[1] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007

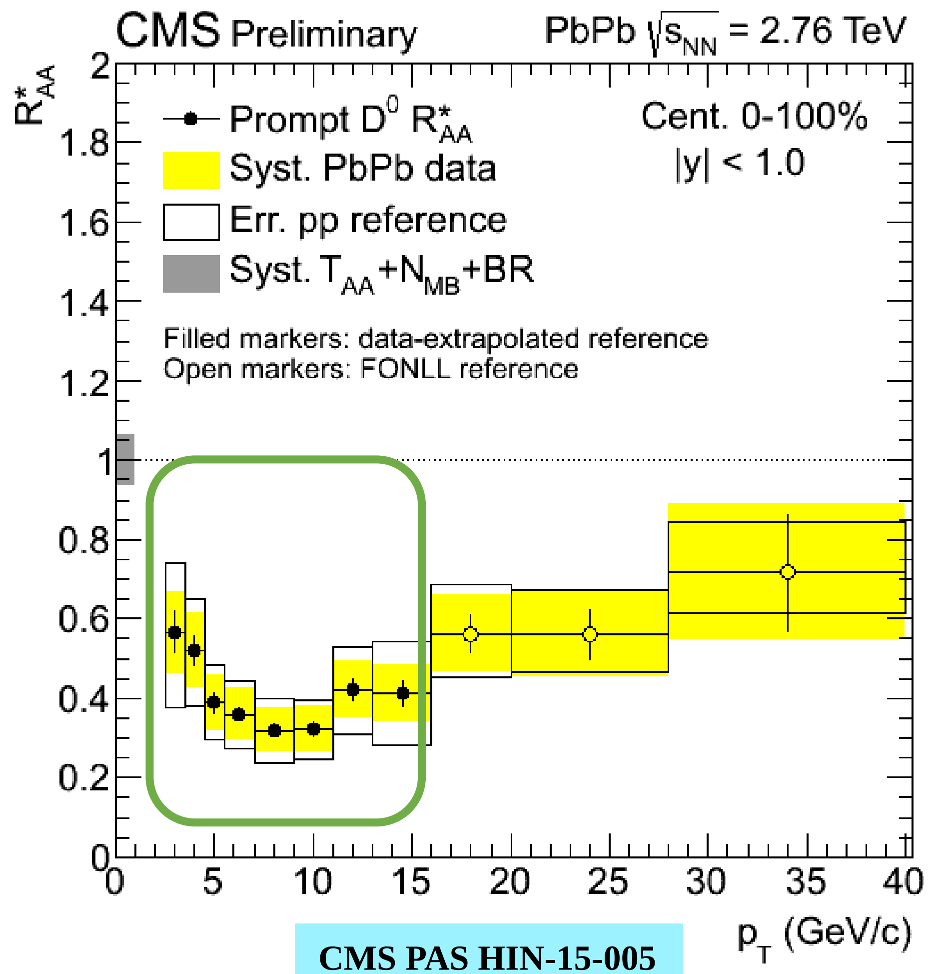
Phys. Rev. Lett. 113, 132301 (2014)

Prompt D^0 Spectrum and R^*_{AA} in Centrality 0-100%

pp reference:

- p_T < 16 GeV, data-extrapolated, scaled from ALICE pp @ 7 TeV [1] with FONLL [2]
- p_T > 16 GeV, FONLL calculation





[1] B. I. Abelev et al. [ALICE Collaboration], JHEP 01 (2012) 128
[2] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007

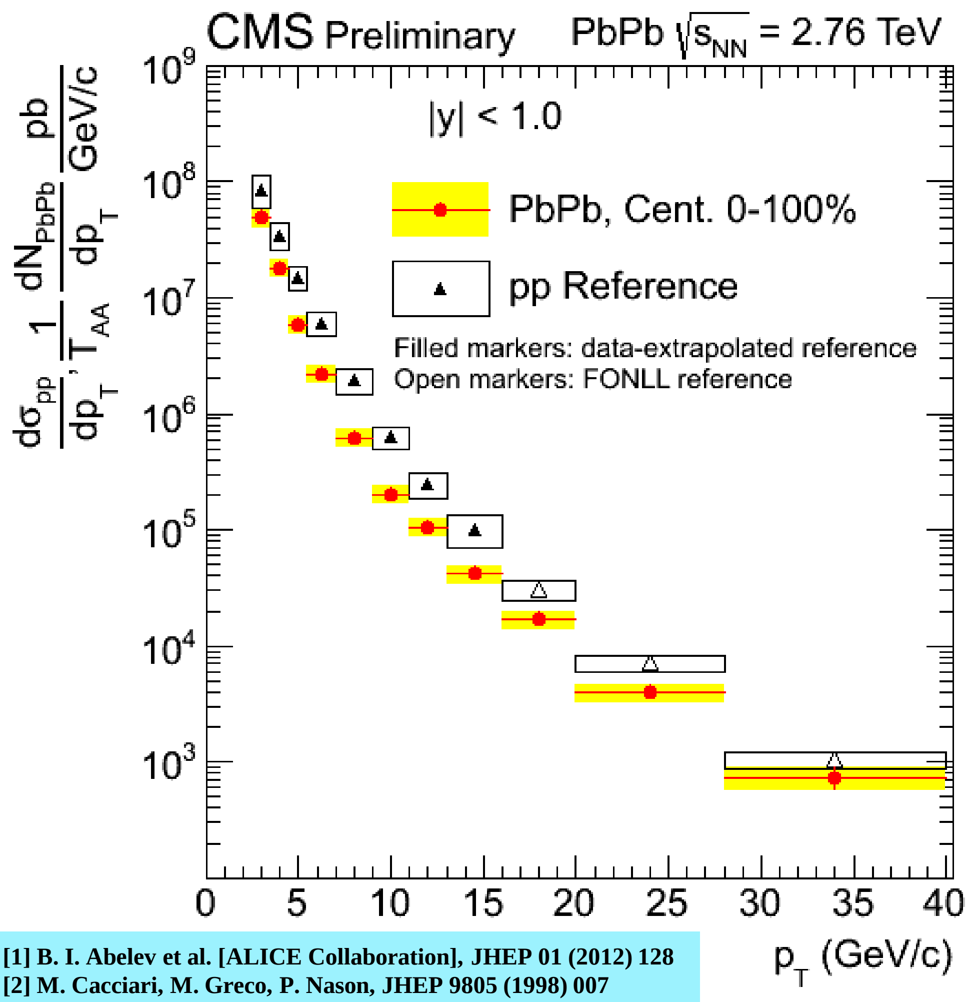
CMS PAS HIN-15-005

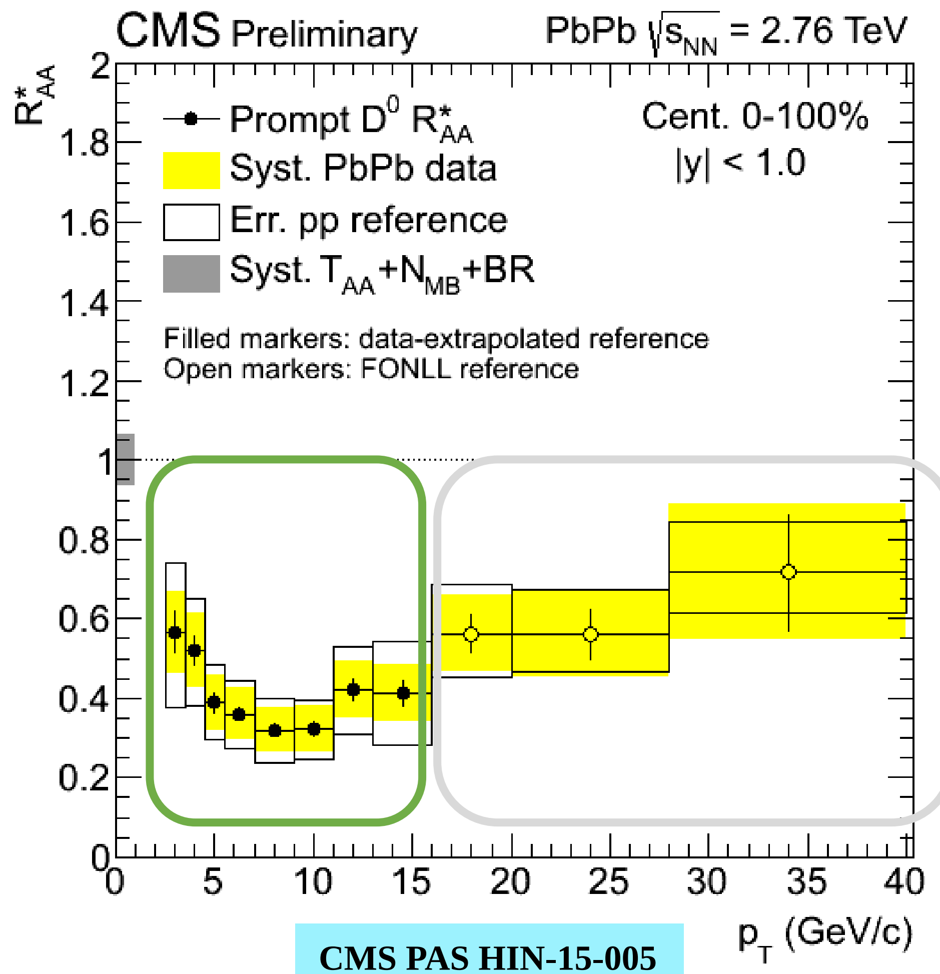
Prompt D^0 Spectrum and R^*_{AA} in Centrality 0-100%

pp reference:

- p_T < 16 GeV, data-extrapolated, scaled from ALICE pp @ 7 TeV [1] with FONLL [2]
- p_T > 16 GeV, FONLL calculation

Prompt D^0 production is strongly suppressed in PbPb collisions



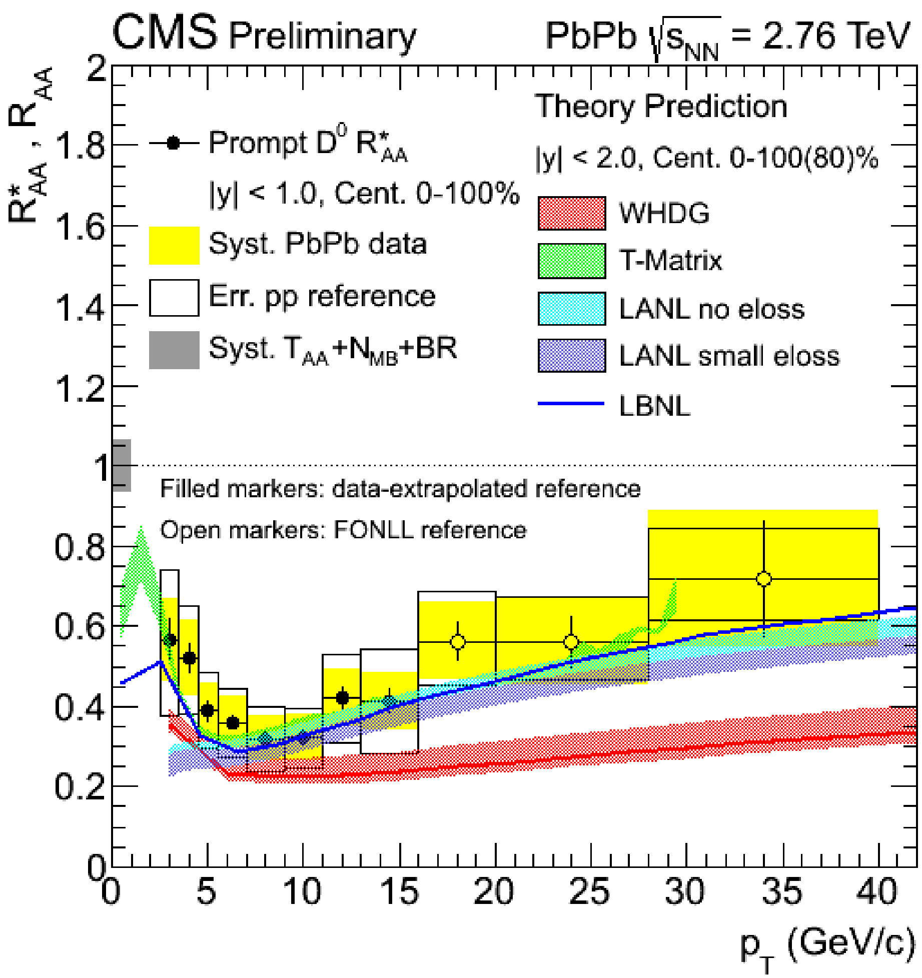


CMS PAS HIN-15-005

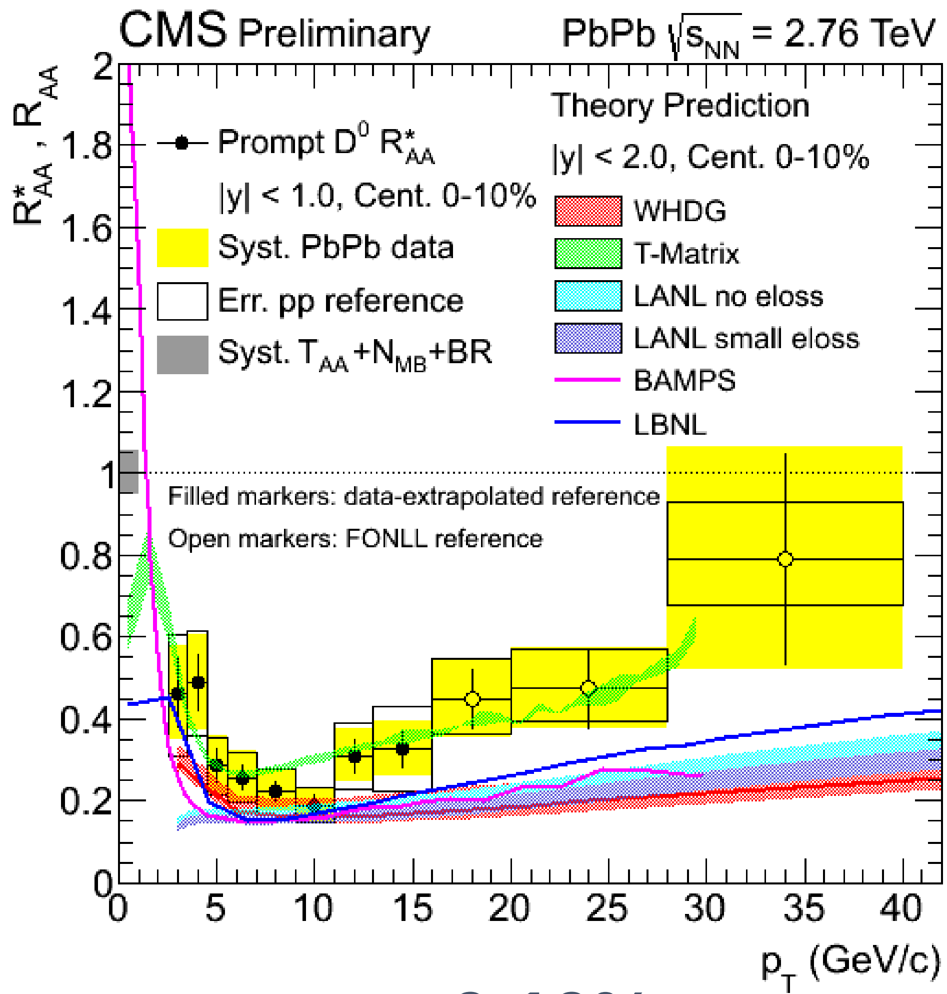
[1] B. I. Abelev et al. [ALICE Collaboration], JHEP 01 (2012) 128
[2] M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007

Comparison with Theoretical Models

CMS PAS HIN-15-005



0-100%

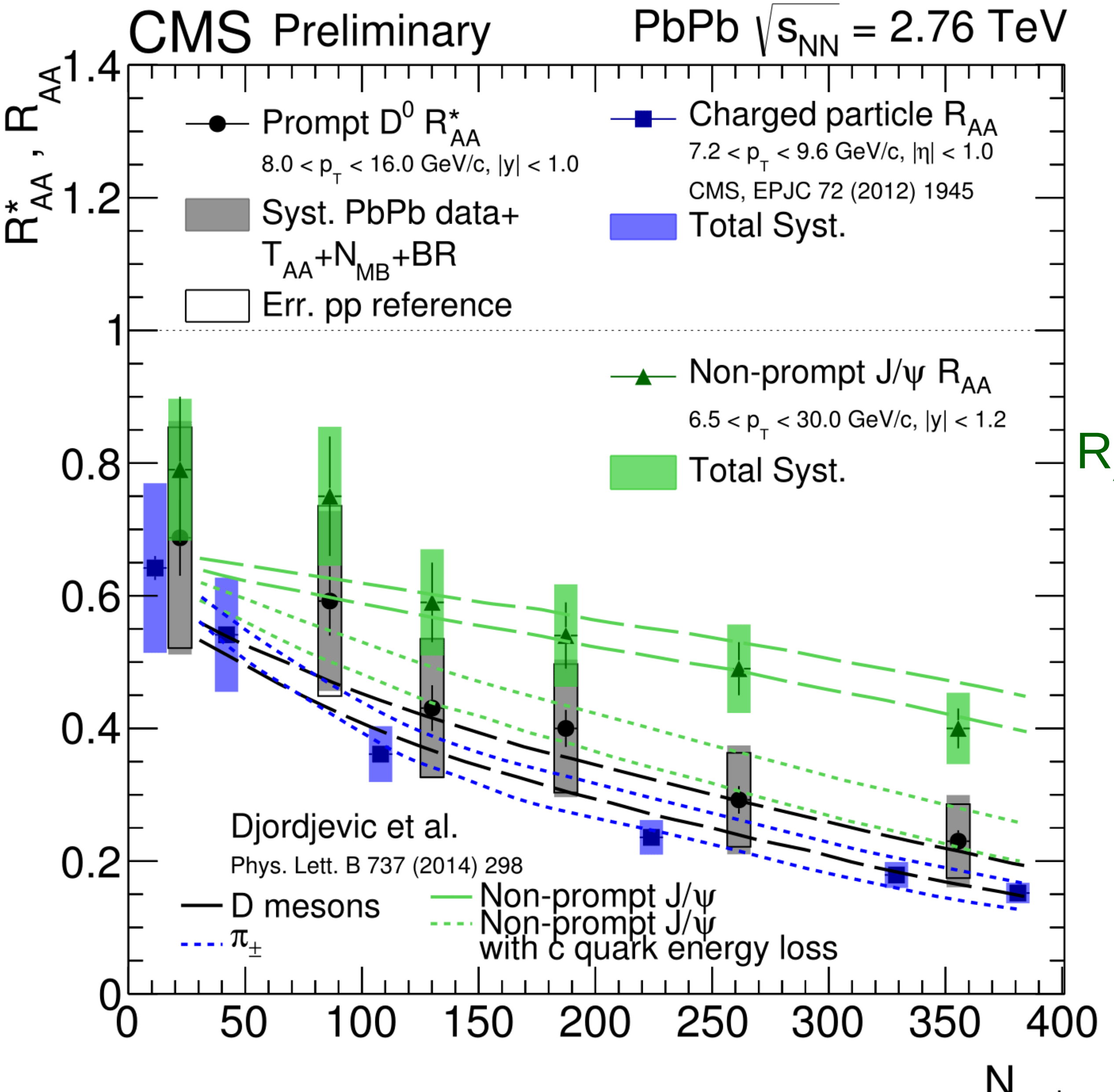


0-10%

WHDG: Horowitz et al., arXiv:1104.4958
T-Matrix: He, Rapp, private communication
LBNL: Cao et al., PRC 92 (2015) 2, 024907, PRC88 (2013) 4, 044907

BAMPS: Uphoff et al., arXiv:1408.2964
LANL: Vitev et al., arXiv:1507.05987, PRC 80 (2009) 054902, PRC 87 (2013) 4, 044905, PRL 114 (2015) 9, 092002

Flavor Dependence of the R_{AA}



Prompt D^0 R^*_{AA}

Charged particle R_{AA}

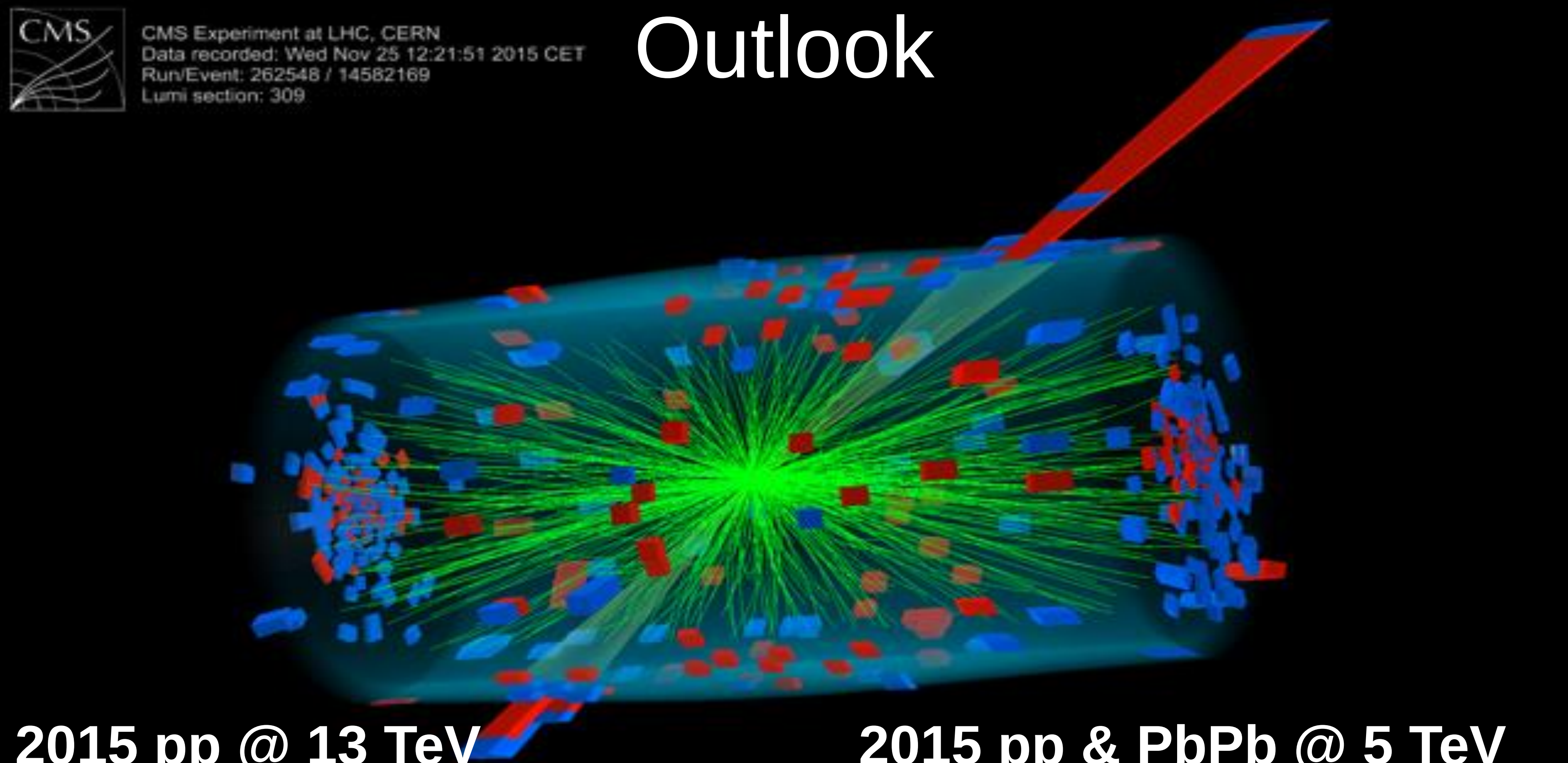
Non-prompt J/ψ R_{AA}

$R_{AA}^{(b\rightarrow J/\psi)} > R_{AA}^{(prompt\ D0)} >= R_{AA}^{(h\pm)}$

The data agree with calculations by Djordjevic et al. within uncertainties

EPJC 72 (2012) 1945 | Djordjevic et al. Phys. Lett. B 737 (2014) 298 | CMS PAS HIN-15-005 | CMS PAS HIN-12-014

Outlook

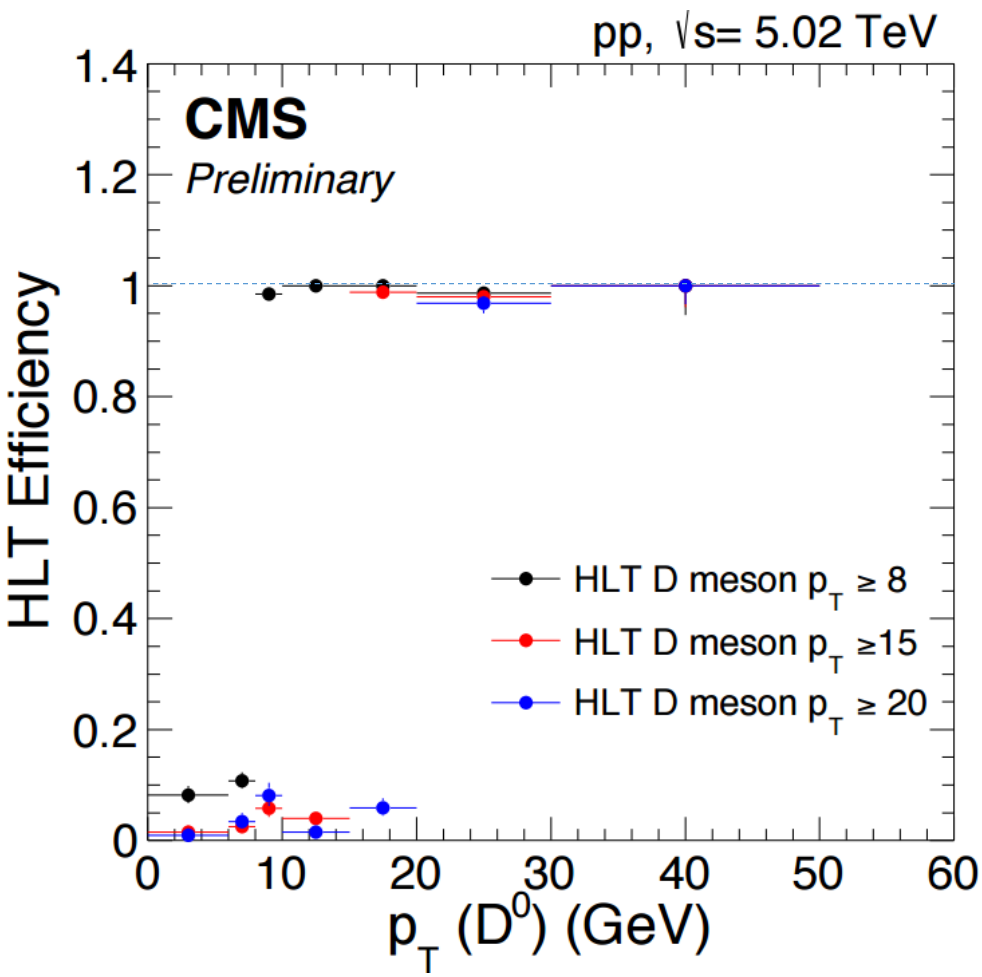


2015 pp @ 13 TeV

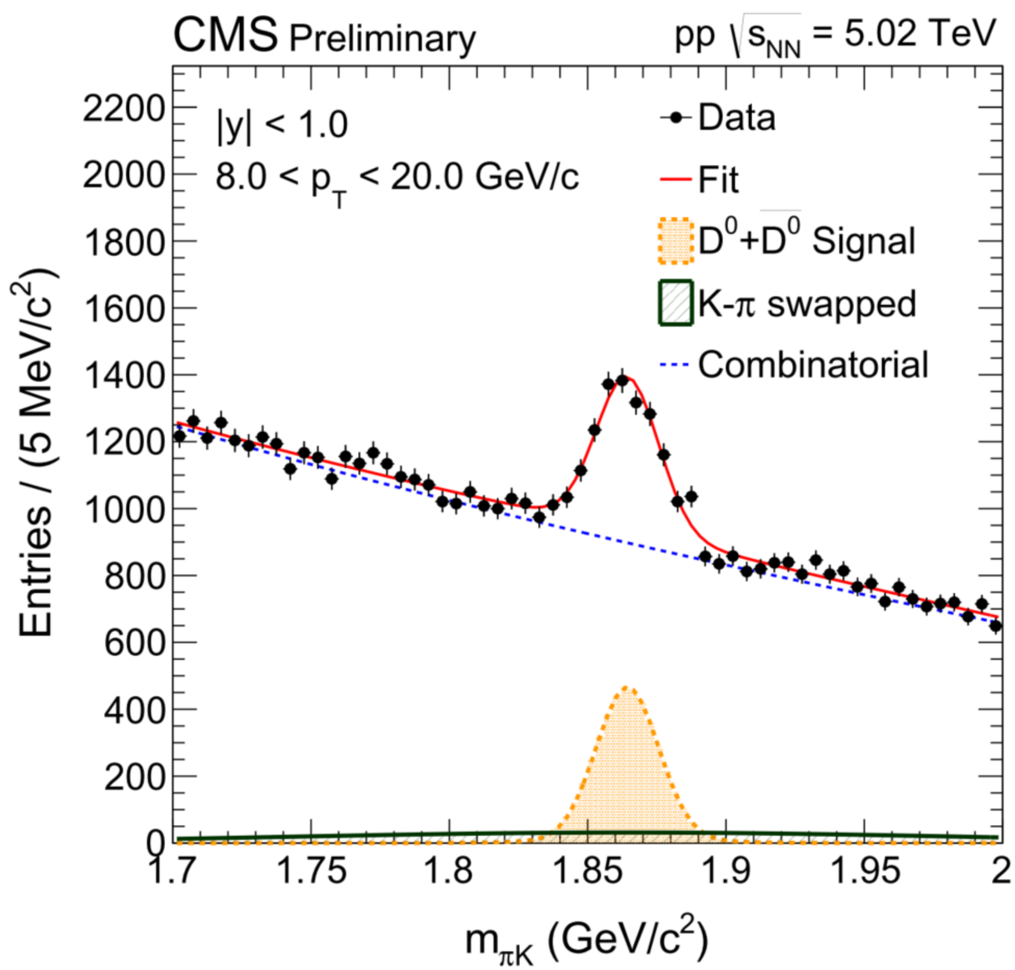
2015 pp & PbPb @ 5 TeV

D^0 and B^+ peak in **proton-proton** collisions @ 5.02 TeV

Excellent D meson trigger efficiency!



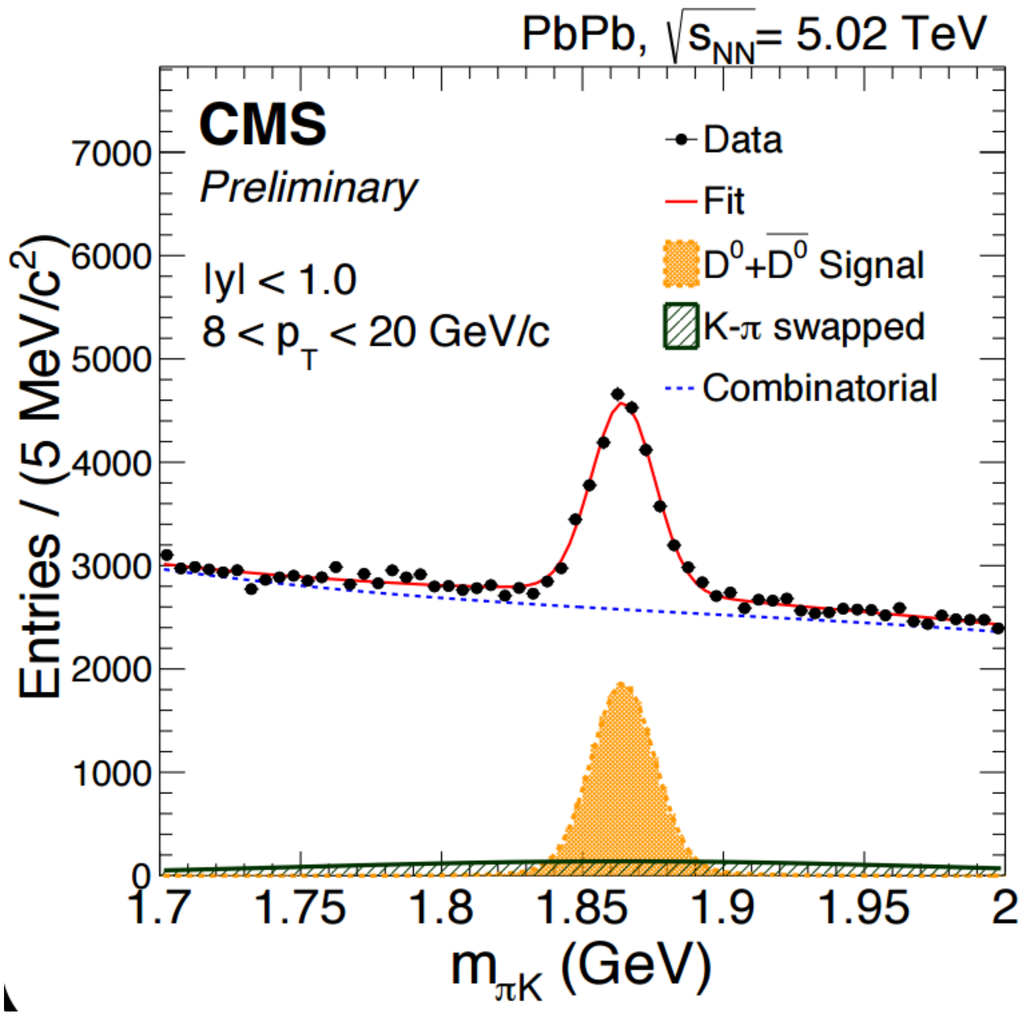
D^0 mesons from online trigger
(Partial statistics)

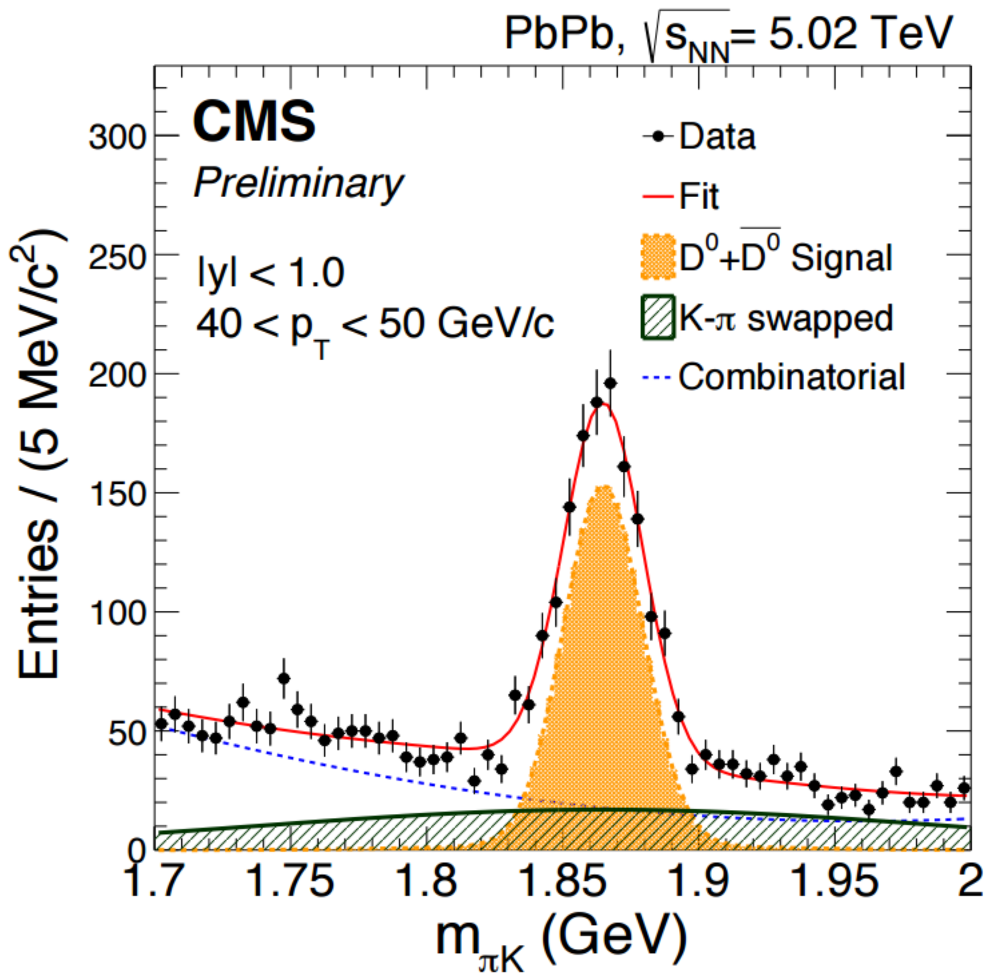


2.5 billion minimum-bias events recorded for low p_T D meson analyses (p_T<20 GeV/c). D^0 meson trigger for high p_T D^0 analyses (p_T> 8 GeV/c)

D^0 and ψ peak in **PbPb** collisions @ 5.02 TeV

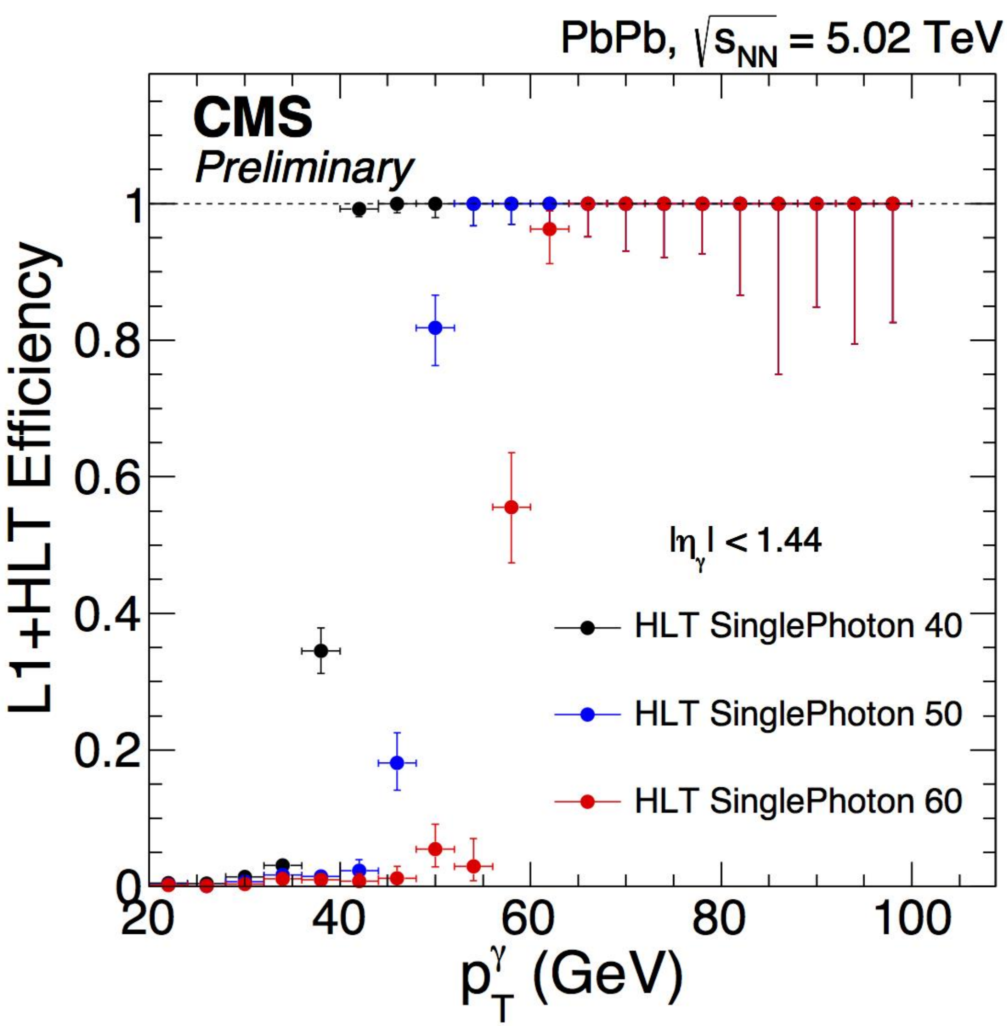
D^0 mesons from minbias and online trigger (partial statistics)



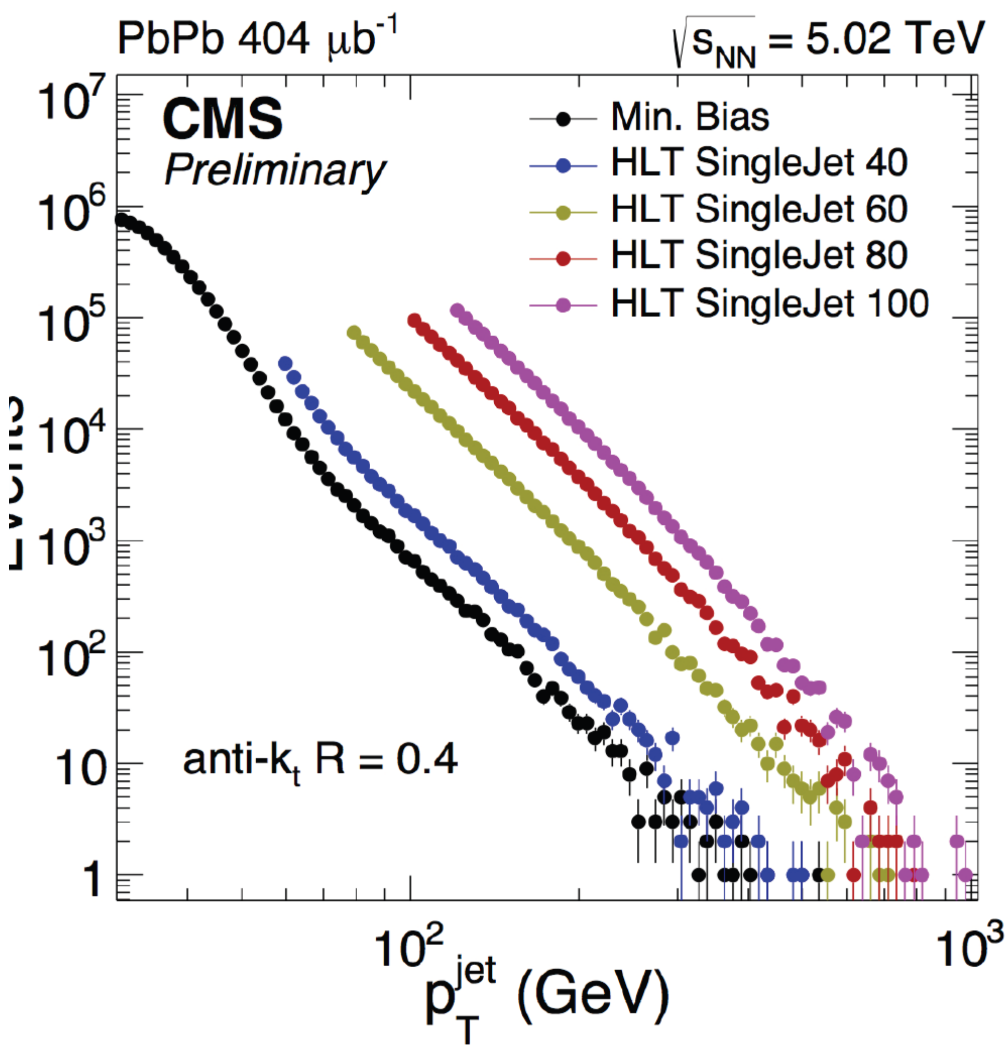


A large minimum bias sample (and centrality triggered sample) is recorded for low p_T D^0, D^+, D^* and D_s analyses

Jets and photons @ 5.02 TeV



Excellent **photon** trigger performance



Extended the **jet** p_T reach to ~ 1 TeV

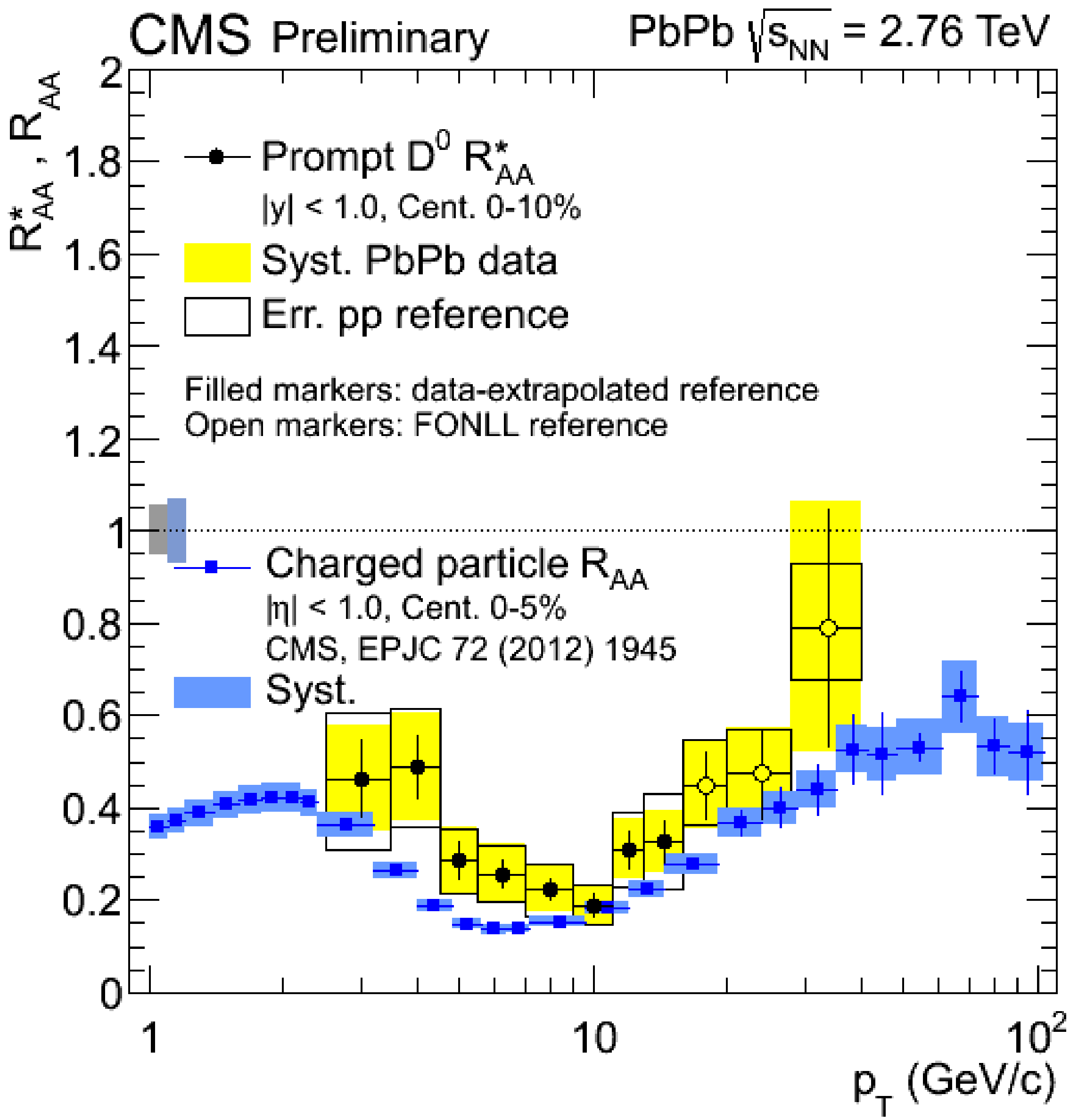
Summary

- CMS has made significant progress on the studies of jet quenching with jets and heavy flavor mesons, in pp, pPb and PbPb collisions

- The direction of the future CMS analyses:
  - Focus on more and more "exclusive" processes and study the event-by-event fluctuation of jet quenching: splitting functions, jet mass, jet width … using jet-track correlation
  - Cover experimental observables with jets and mesons for the study of flavor dependence of the jet quenching

- Backup slides

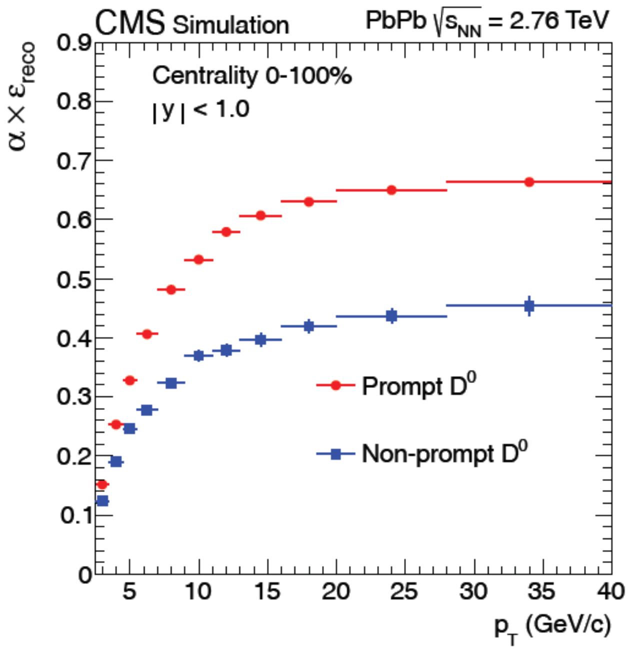
Comparison with charged particle R_{AA}



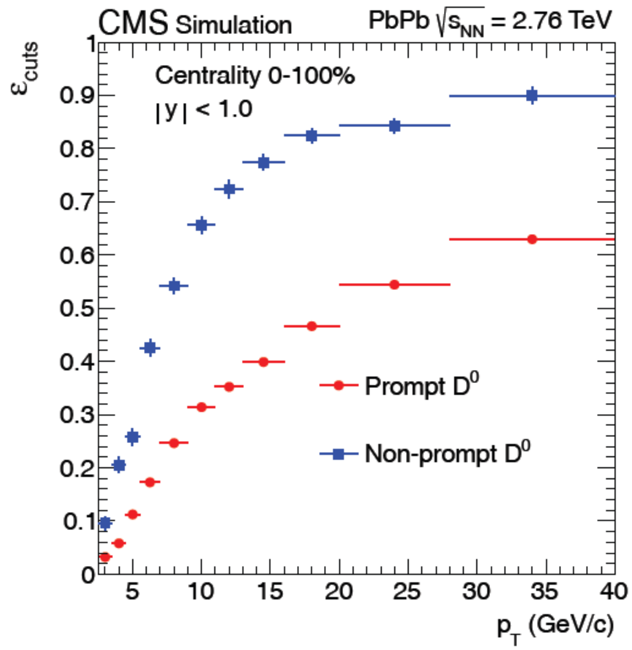
EPJC 72 (2012) 1945

CMS PAS HIN-15-005

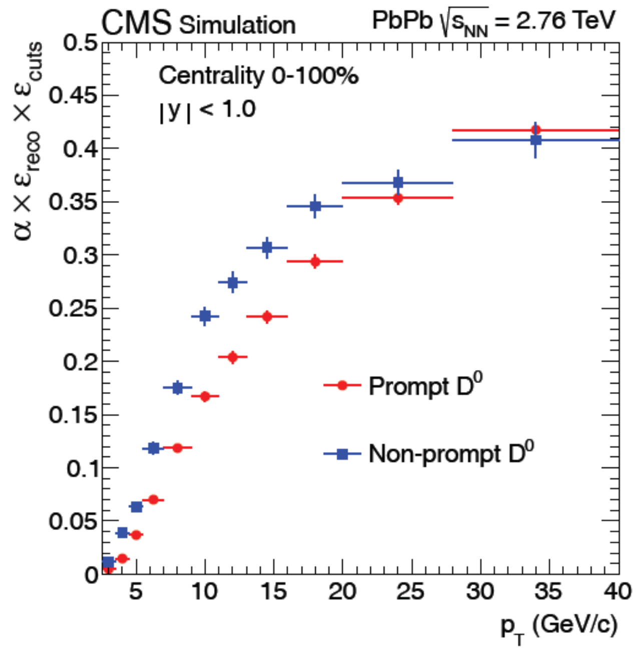
Efficiency and Acceptance Correction



Reconstruction

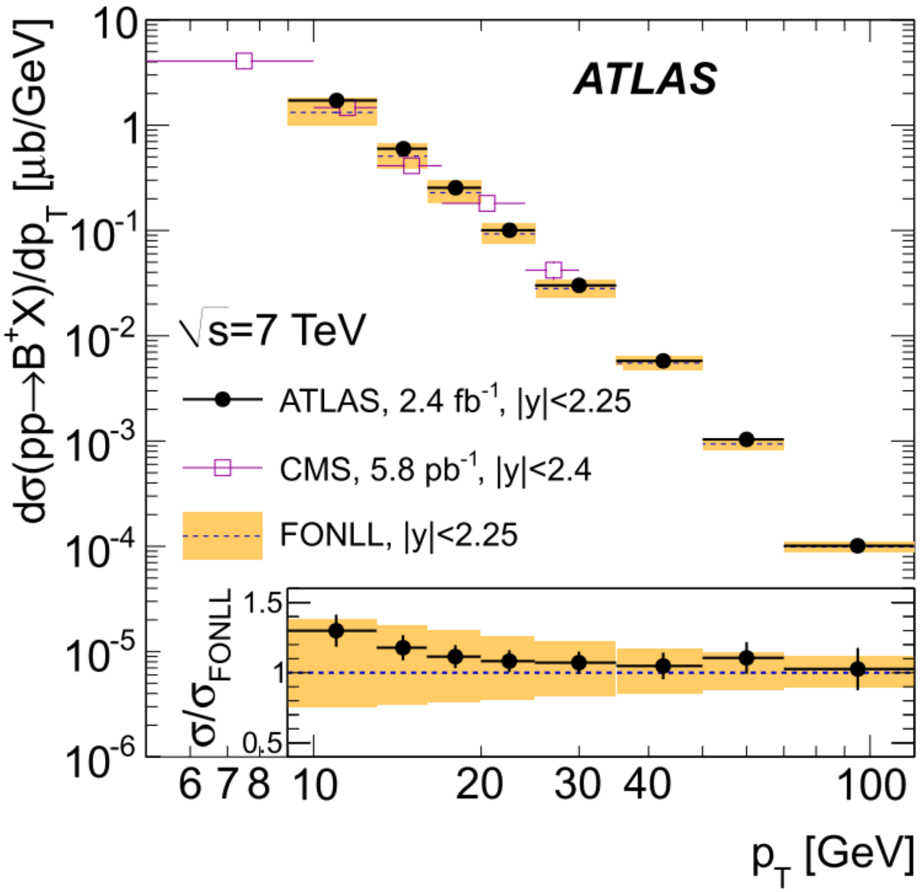


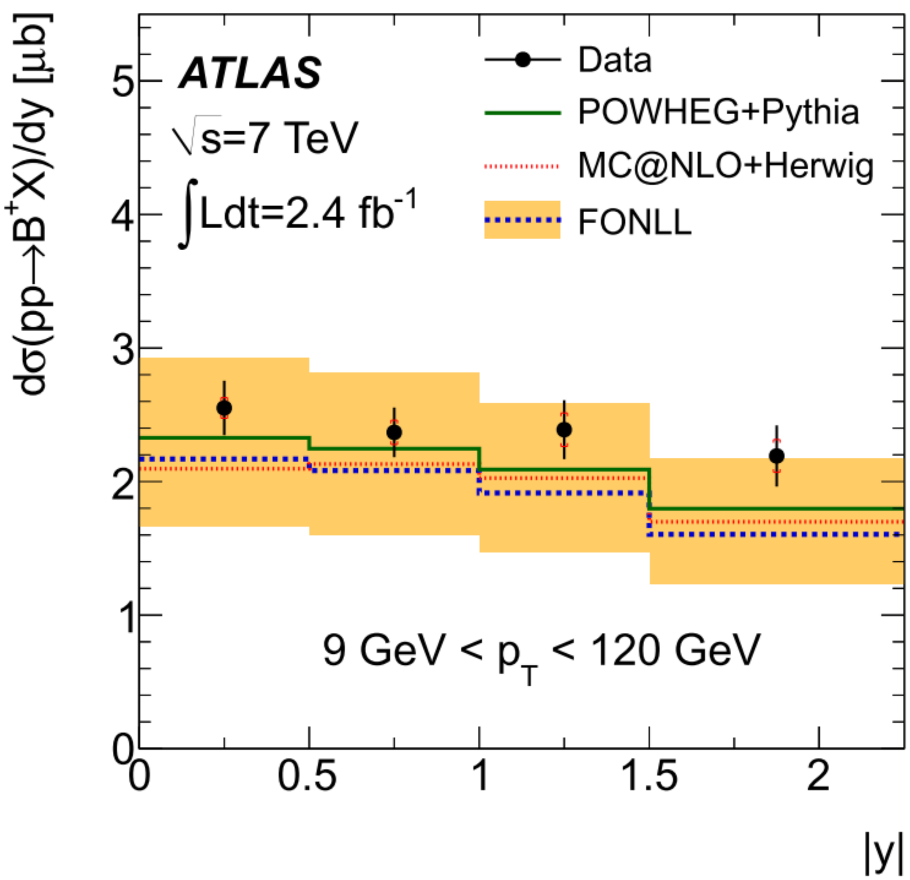
D meson selection

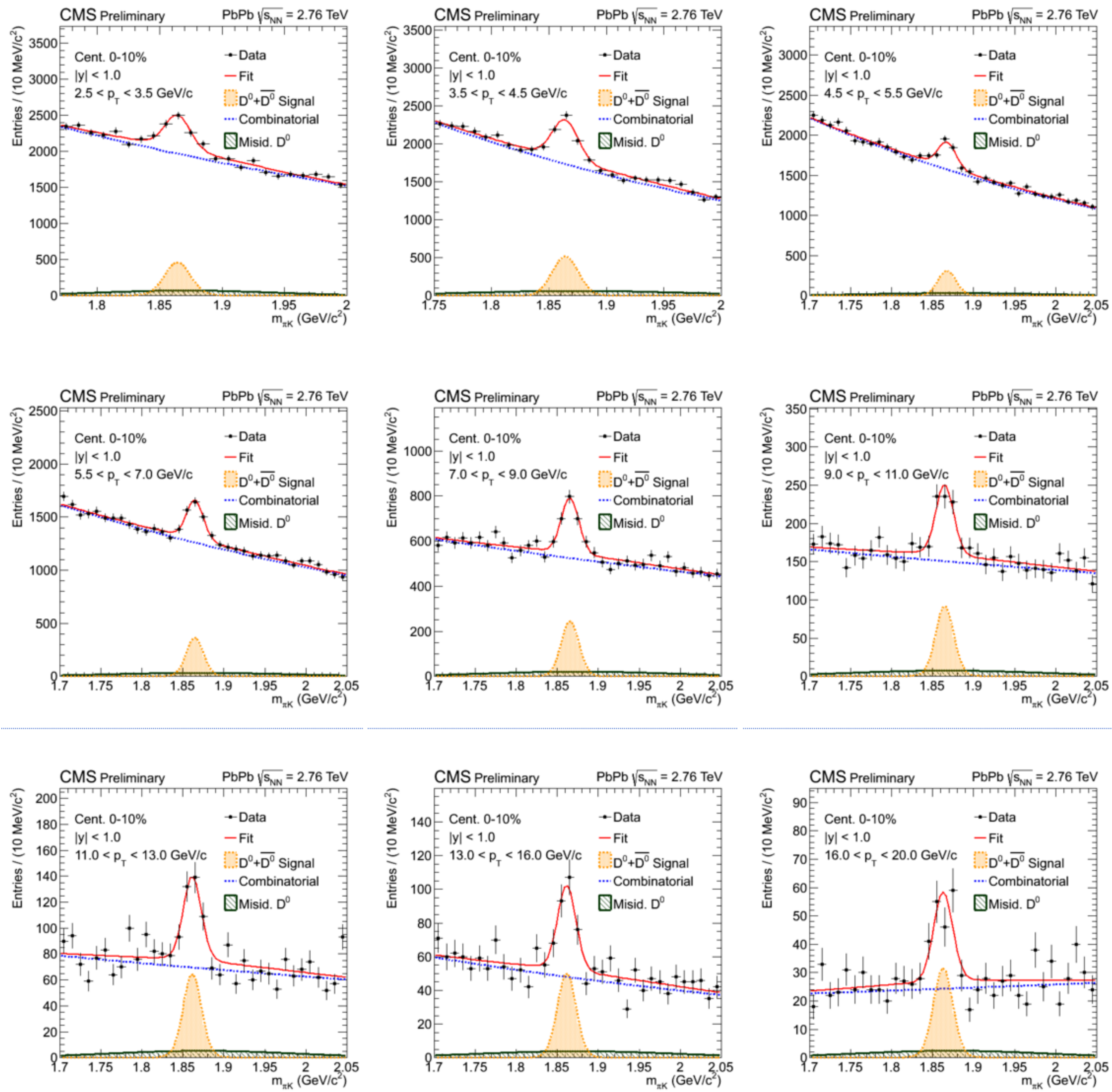


Full eff x acc

ATLAS result at 7 TeV

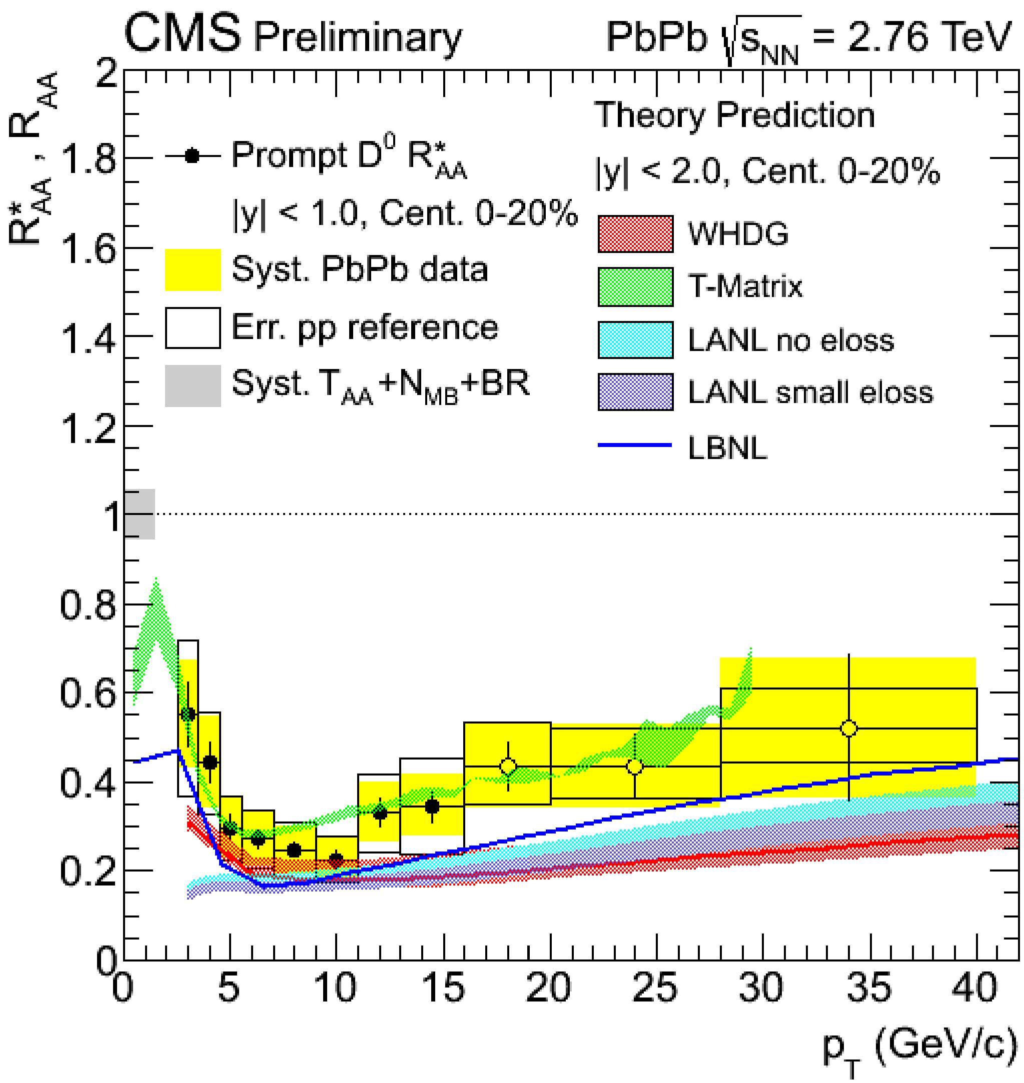






CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Cent. 0-10%
|y| < 1.0
2.5 < p_T < 3.5 GeV/c
3.5 < p_T < 4.5 GeV/c
4.5 < p_T < 5.5 GeV/c
5.5 < p_T < 7.0 GeV/c
7.0 < p_T < 9.0 GeV/c
9.0 < p_T < 11.0 GeV/c
11.0 < p_T < 13.0 GeV/c
13.0 < p_T < 16.0 GeV/c
16.0 < p_T < 20.0 GeV/c
Data
Fit
$D^0+\overline{D^0}$ Signal
Combinatorial
Misid. D^0
Entries / (10 MeV/c^2)
$m_{\pi K}$ (GeV/c^2)

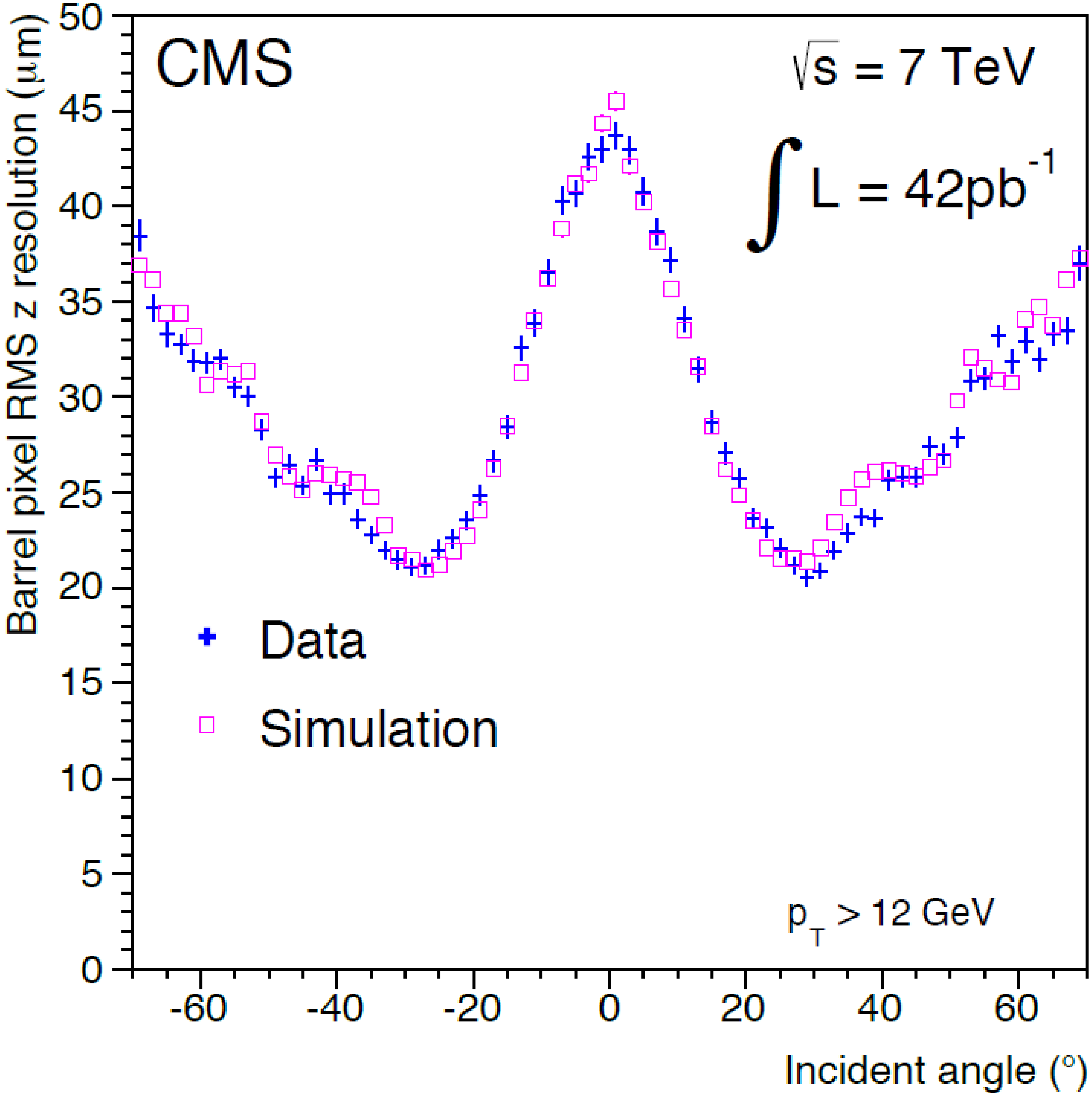
Nuclear Modification Factors:



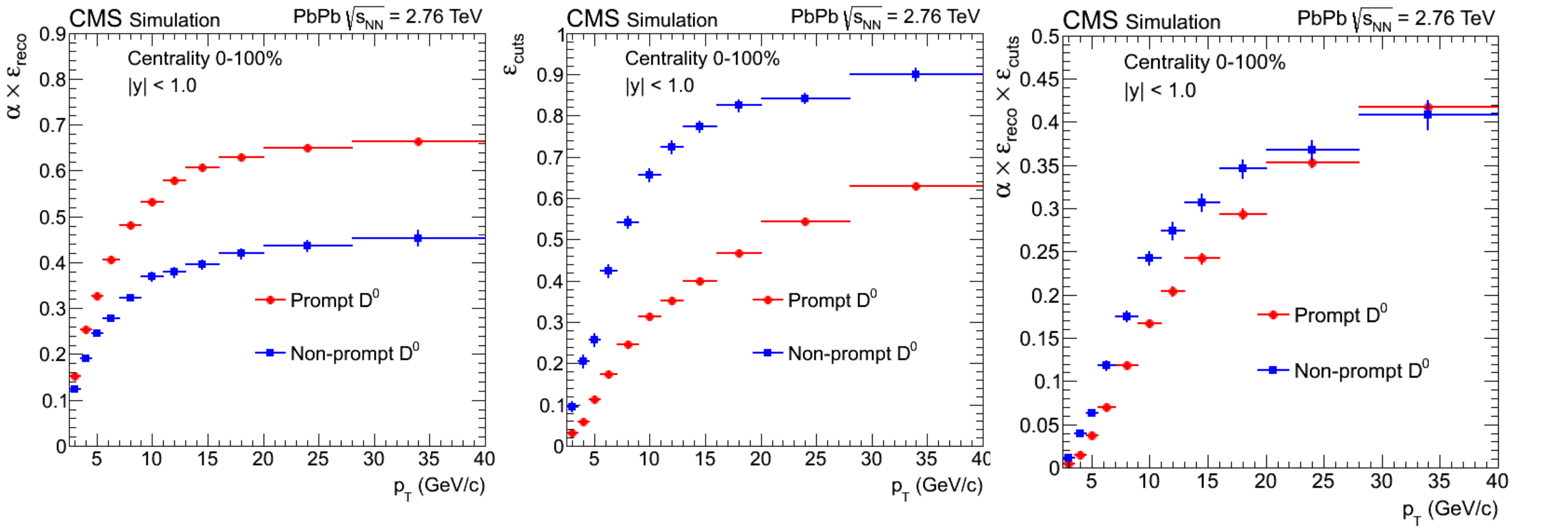
Information for pPb Analysis

- CMS experiments of pPb collision in 2013
  - LHC delivered 4TeV (p) and 1.58 TeV/nucleon (Pb) beam
  - Integrated luminosity : 34.8 nb^{-1}
  - rapidity boosted to proton going side(forward) by 0.465 in lab frame
- Charged B, B_0, B_s trio are measured vi J/ψ decay channels
- Kinematic range covered
  - p_T : 10 – 60 GeV/c
  - rapidity : $|y_{CM}|<1.93$
- B^+ and B^- are inclusively measured and expressed as B^+ from now on

Hit Position Resolution



Acceptance and efficiency correction



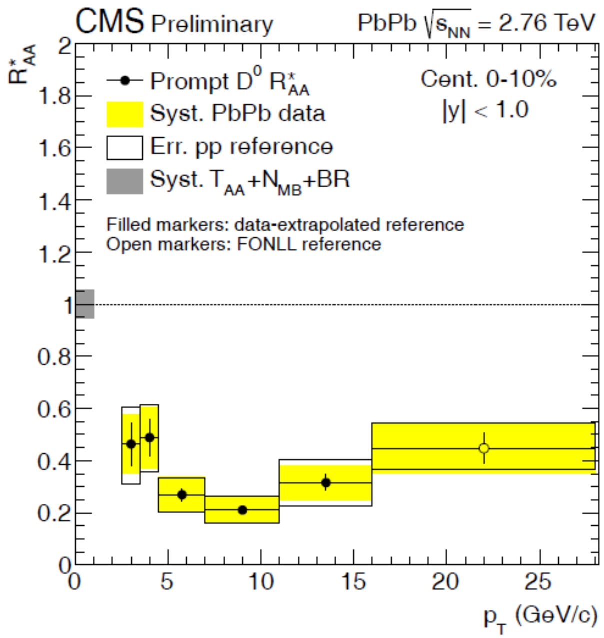
- **a × e_{reco}: prompt D0 higher than non-prompt D0 (D0 from B-hadron decay)**
  - ➢ Tracks from non-prompt D^0 are more displaced from primary vertex than tracks from prompt D^0
  - ➢ Hi tracking has lower efficiency on further displaced tracks

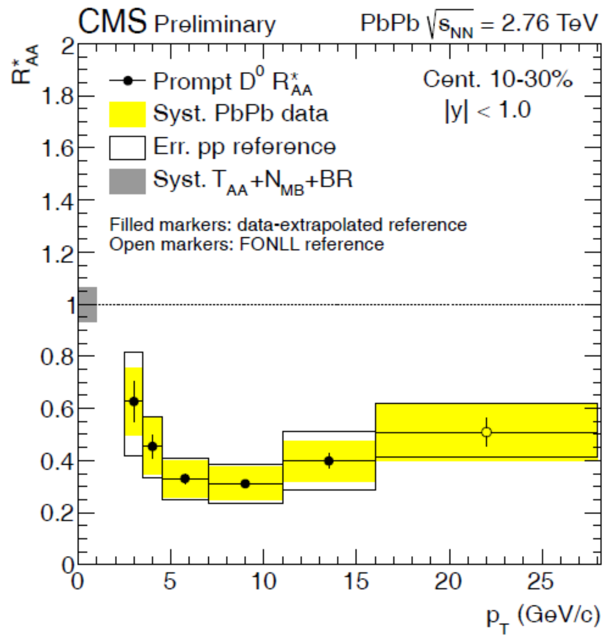
- **e_{cuts}: non-prompt D0 higher than prompt D0**
  - ➢ Non-prompt D^0 are more displaced from primary vertex than prompt D^0, thus bigger d0/error_d0

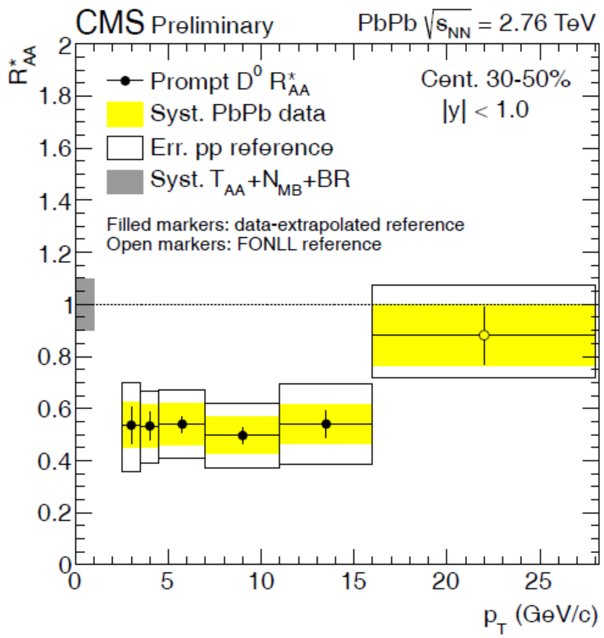
CMS PAS HIN-15-012

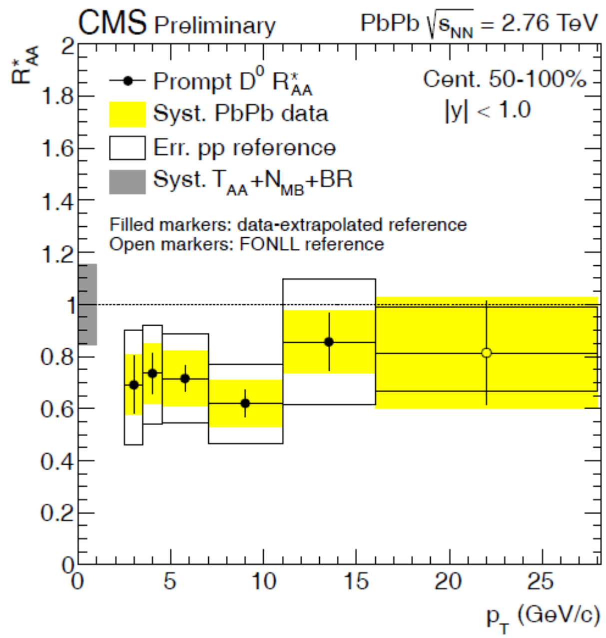
p_T (**GeV/c**)	$d_0/\sigma(d_0)$	α (radians)	**Vertex Probability**
2.5-3.5	> 5.90	< 0.12	> 0.248
3.5-4.5	> 5.81	< 0.12	> 0.200
4.5-5.5	> 5.10	< 0.12	> 0.191
5.5-7.0	> 4.62	< 0.12	> 0.148
7.0-9.0	> 4.46	< 0.12	> 0.102
9.0-11.0	> 4.39	< 0.12	> 0.080
11.0-13.0	> 4.07	< 0.12	> 0.073
13.0-16.0	> 3.88	< 0.12	> 0.060
16.0-20.0	> 3.67	< 0.12	> 0.055
20.0-28.0	> 3.25	< 0.12	> 0.054
28.0-40.0	> 2.55	< 0.12	> 0.050

Table 1: Summary table of the selection criteria in different p_T intervals.


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Prompt D^0 R^*_{AA}
Syst. PbPb data
Err. pp reference
Syst. T_{AA}+N_{MB}+BR
Cent. 0-10%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R^*_{AA}
p_T (GeV/c)

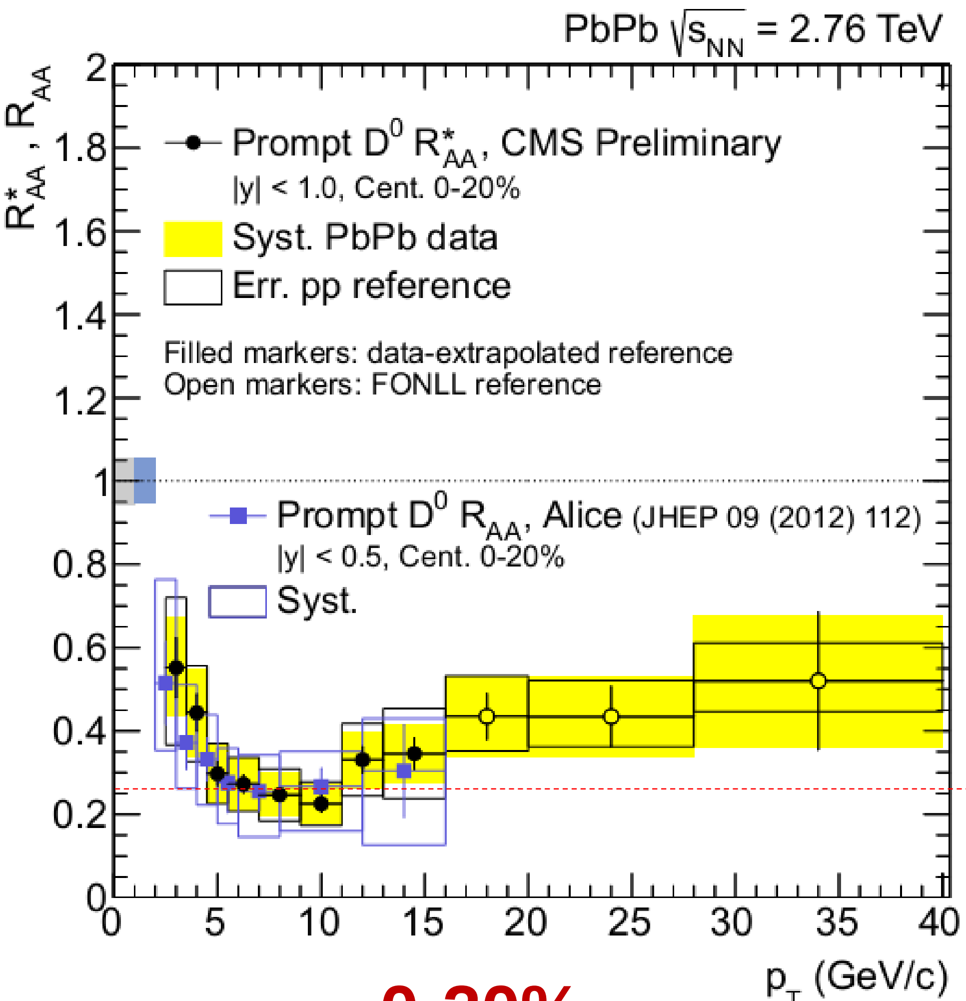

CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Prompt D^0 R^*_{AA}
Syst. PbPb data
Err. pp reference
Syst. T_{AA}+N_{MB}+BR
Cent. 10-30%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R^*_{AA}
p_T (GeV/c)

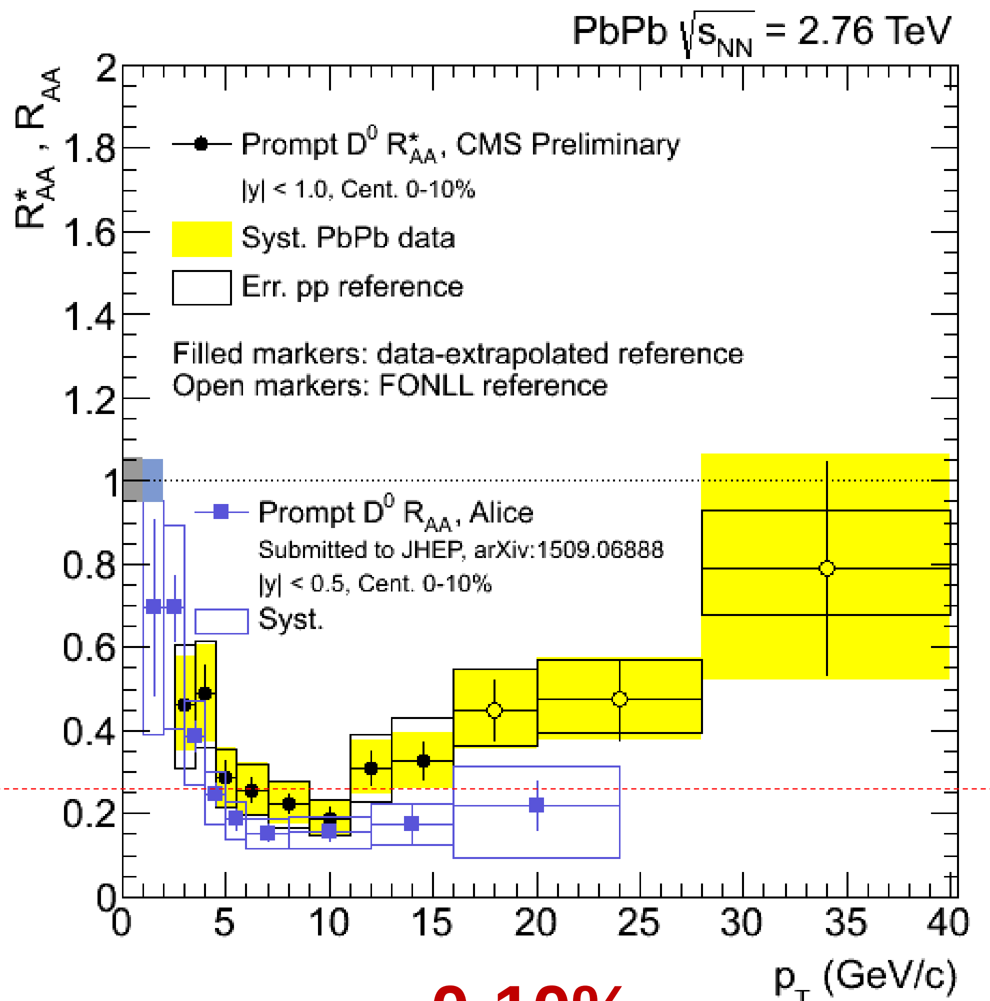

CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Prompt D^0 R^*_{AA}
Syst. PbPb data
Err. pp reference
Syst. T_{AA}+N_{MB}+BR
Cent. 30-50%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R^*_{AA}
p_T (GeV/c)


CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 2.76 TeV
Prompt D^0 R^*_{AA}
Syst. PbPb data
Err. pp reference
Syst. T_{AA}+N_{MB}+BR
Cent. 50-100%
|y| < 1.0
Filled markers: data-extrapolated reference
Open markers: FONLL reference
R^*_{AA}
p_T (GeV/c)

CMS vs. ALICE Results

CMS PAS HIN-15-005





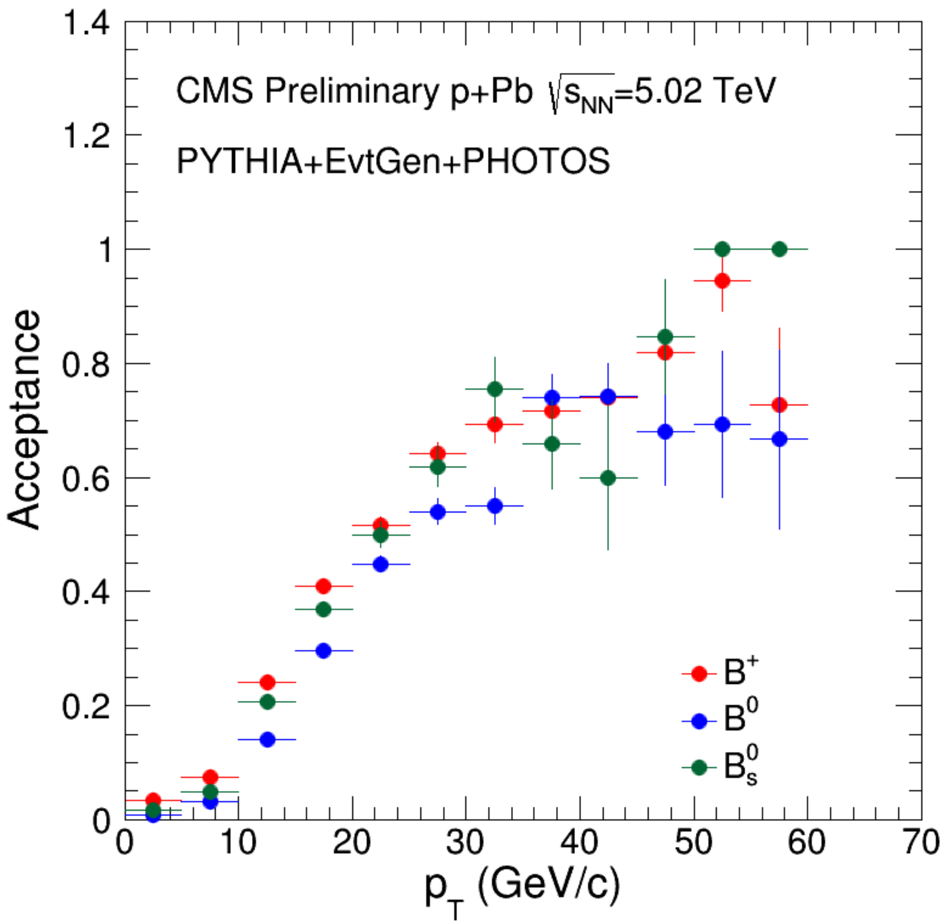
0-20% **0-10%**

For p_T > 16 GeV, differences in pp reference should be taken into account

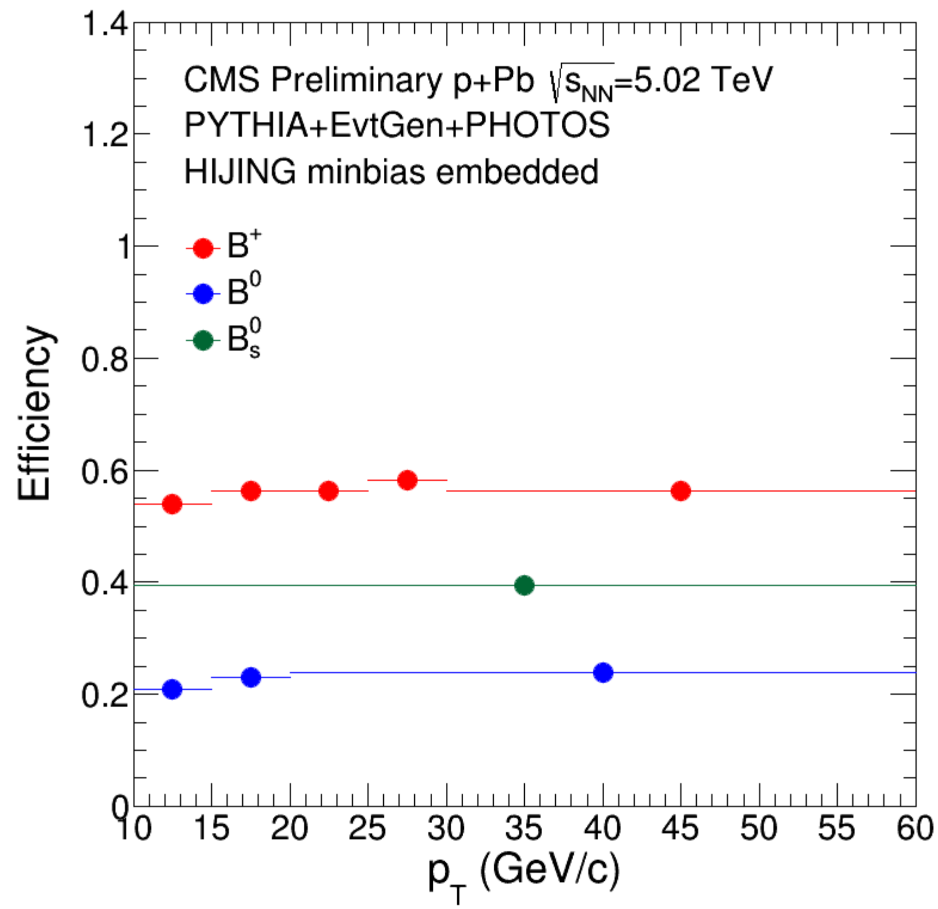
B Meson Acceptance and Efficiency

- Raw yields are corrected by acceptance and efficiency

Acceptance



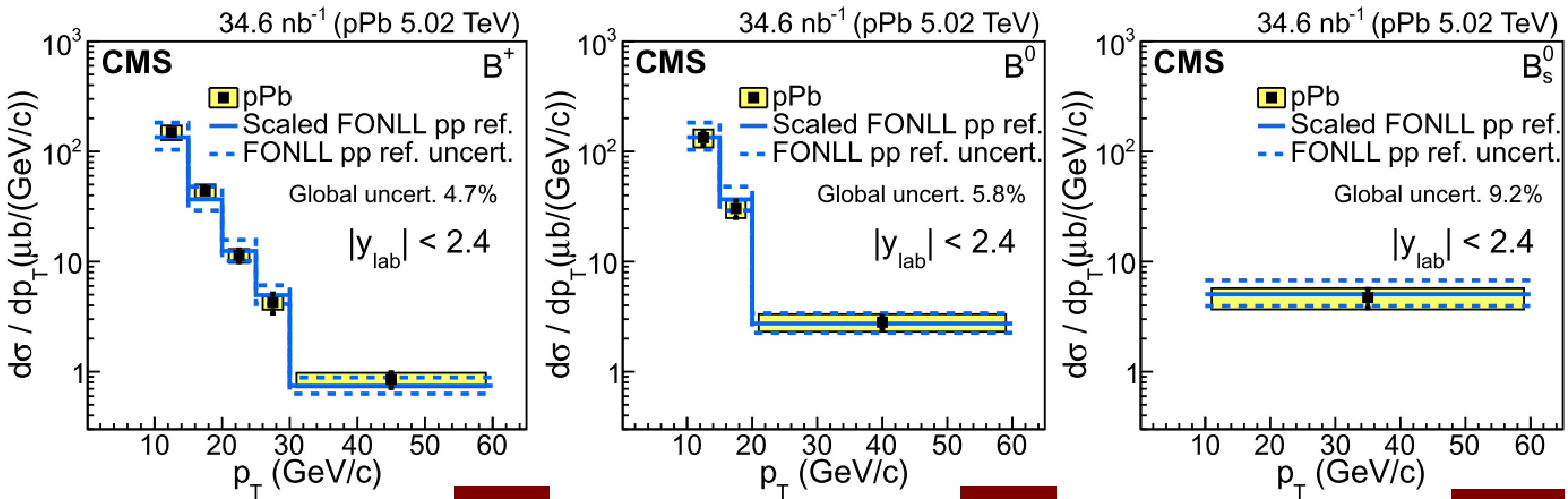
Efficiency



Differential Cross-section in pPb @ 5 TeV

$$\left.\frac{d\sigma^{B}}{dp_T}\right|_{|y_{CM}|<2.4} = \frac{1}{2}\frac{1}{\Delta y\,\Delta p_T}\frac{\left.N^{B}\right|_{|y_{CM}|<2.4}}{(\mathrm{Acc}\times\epsilon)\cdot\mathrm{BR}\cdot L_{\mathrm{int}}}.$$

- pp reference : FONLL expectation is used
  - agreement with CDF and CMS(ATLAS) data
  - calculated in **http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html**

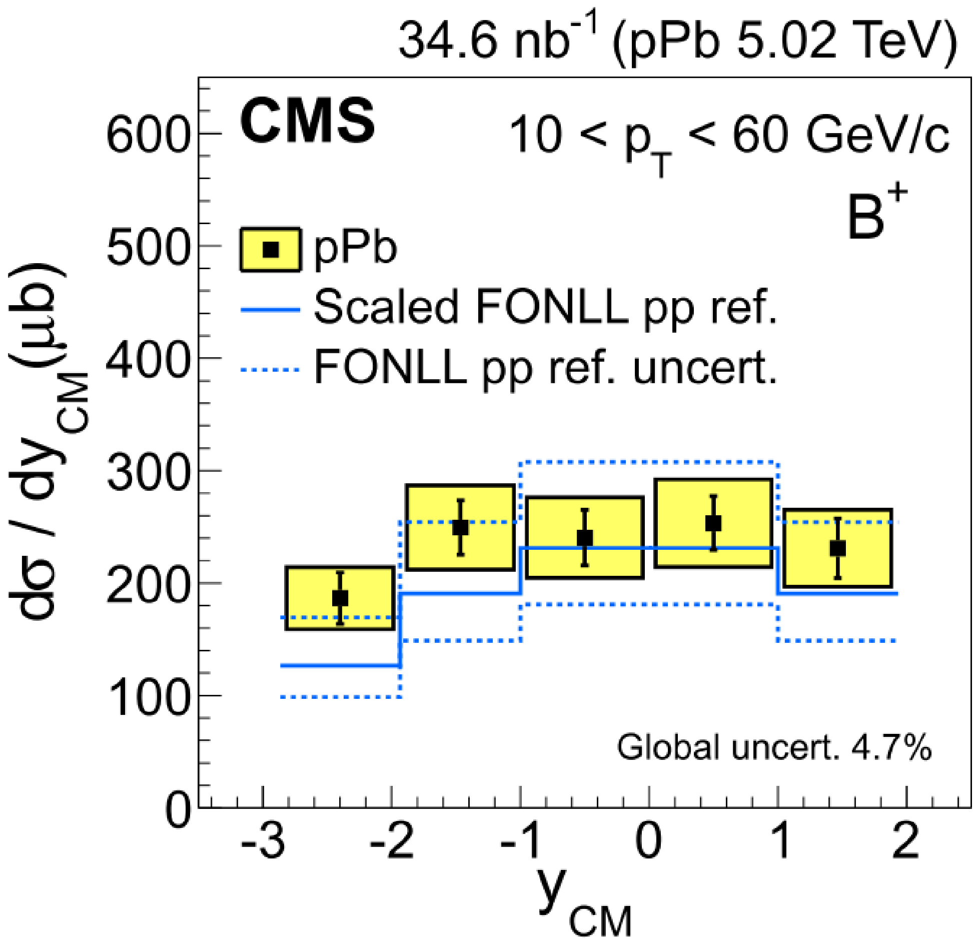


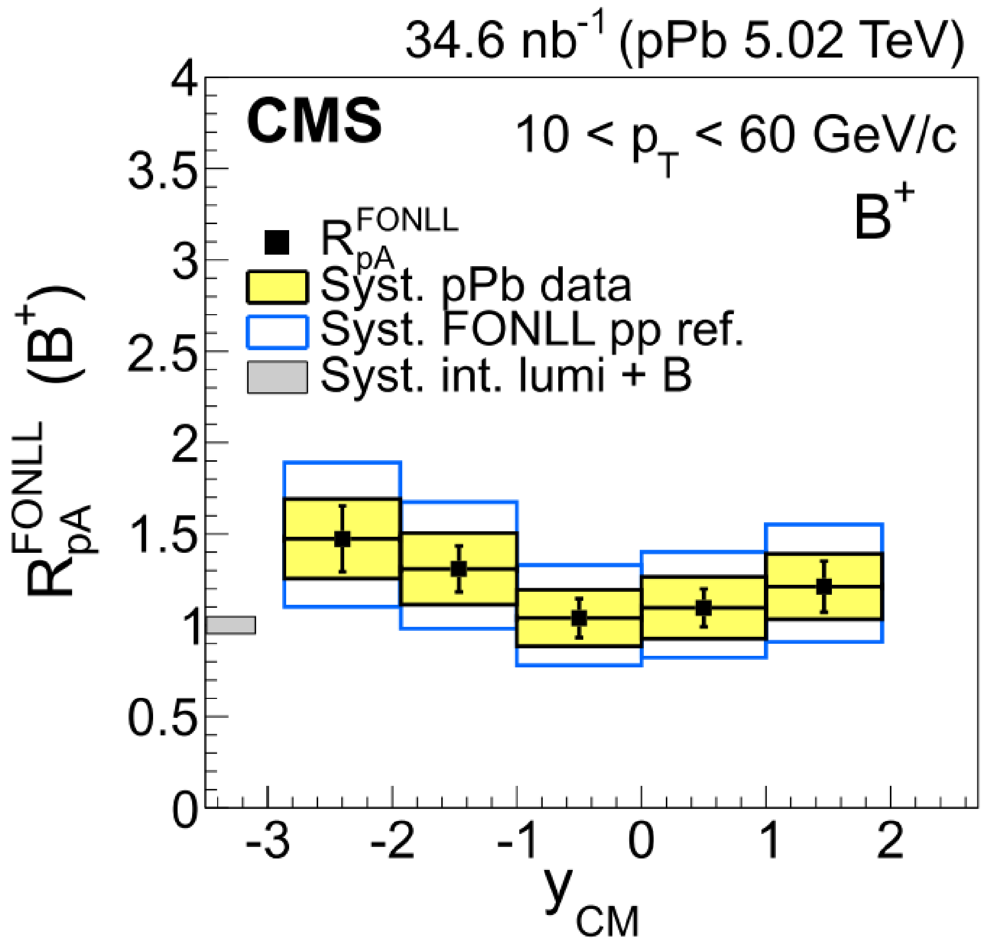
B^+ **B^0** **B^0_s**

Rapidity Distribution in pPb @ 5 TeV

- Rapidity dependence of B^+ production

B^+

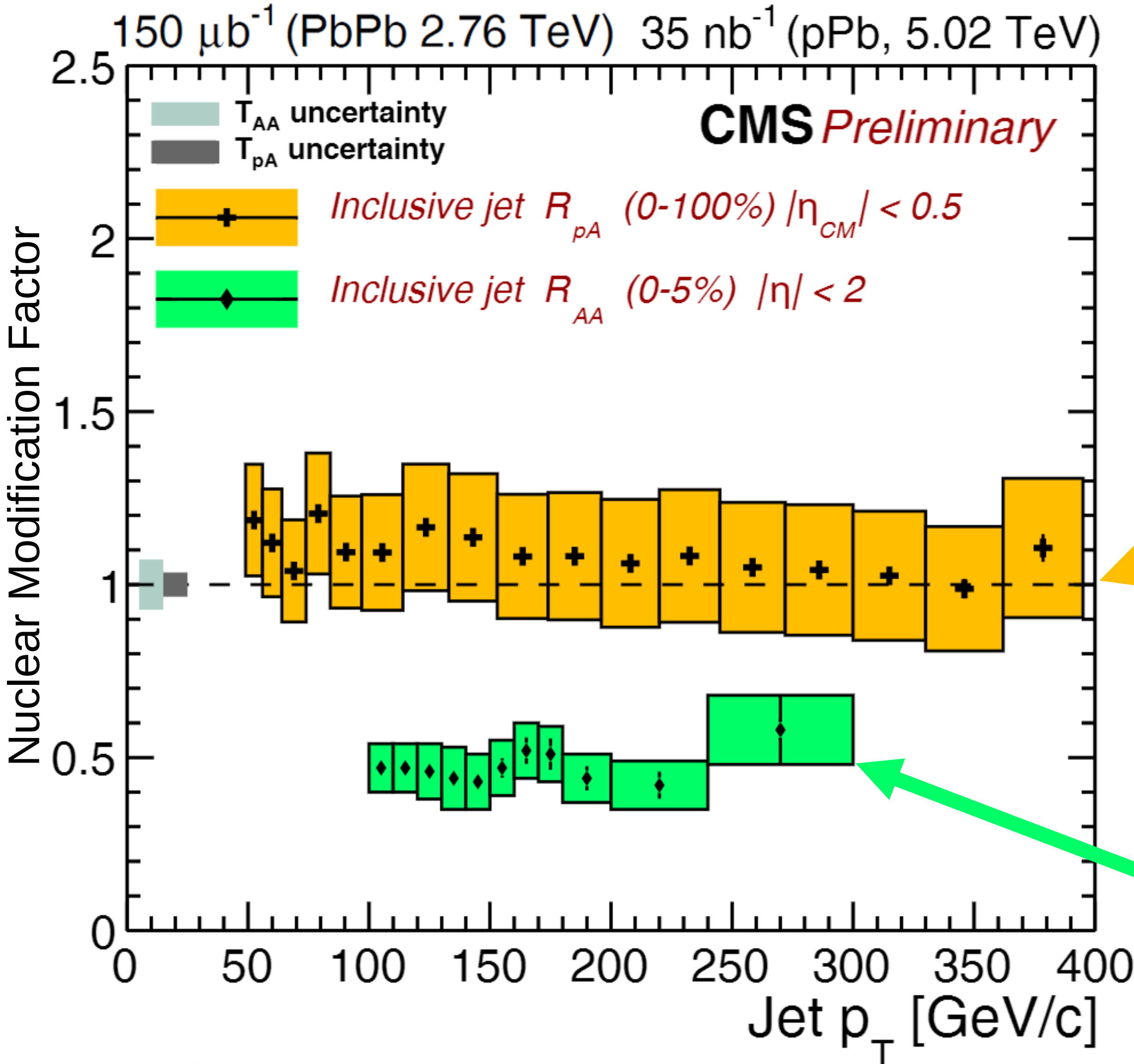




R_{pA}^{FONLL} is compatible with unity within theoretical and experimental uncertainties

PRL 116 (2016) 032301

Jet Transverse Momentum Spectra



Nuclear Modification Factor (R_{AA}):

Ratio of the jet cross-section in **PbPb** and **pp** scaled by the number of nucleon-nucleon collisions

pPb Collisions
No significant modification

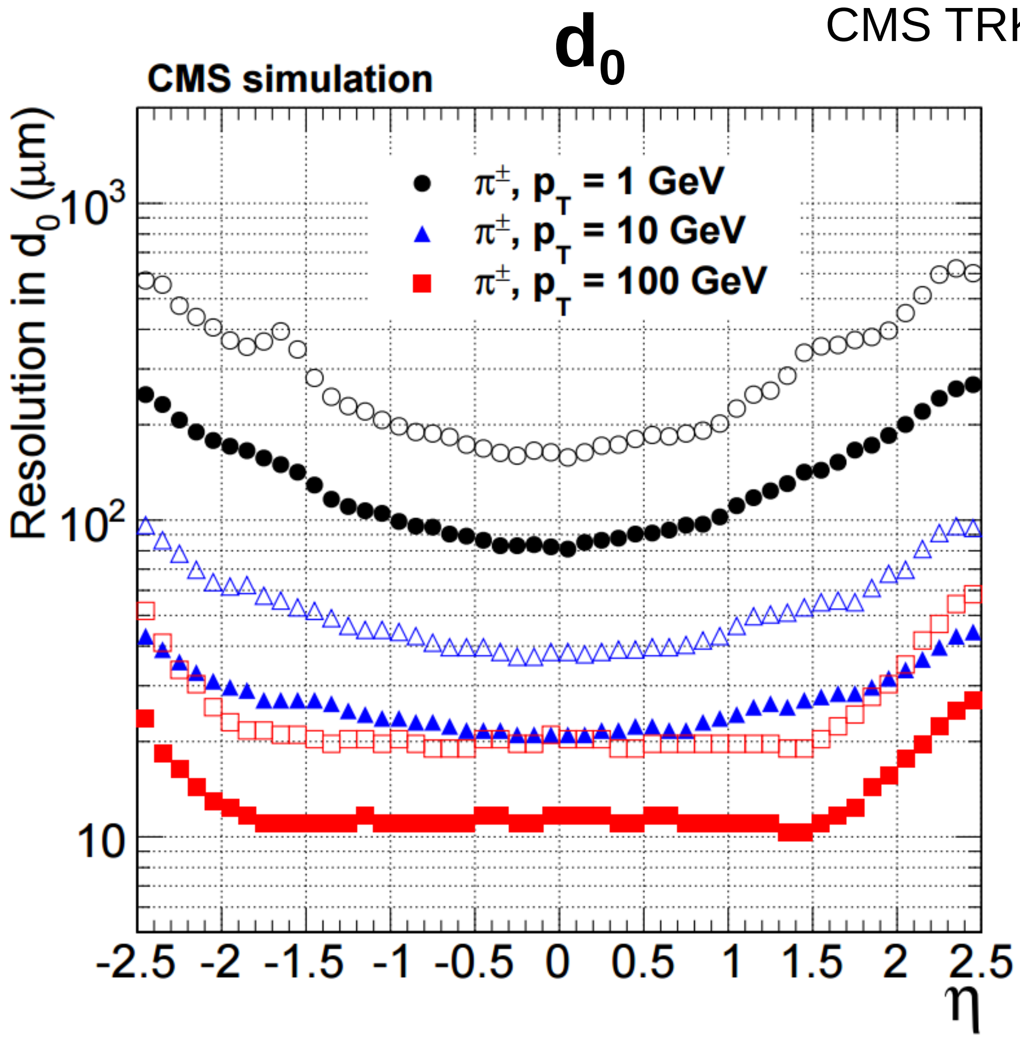
Head-on PbPb Collisions
Large suppression of high p_T jet

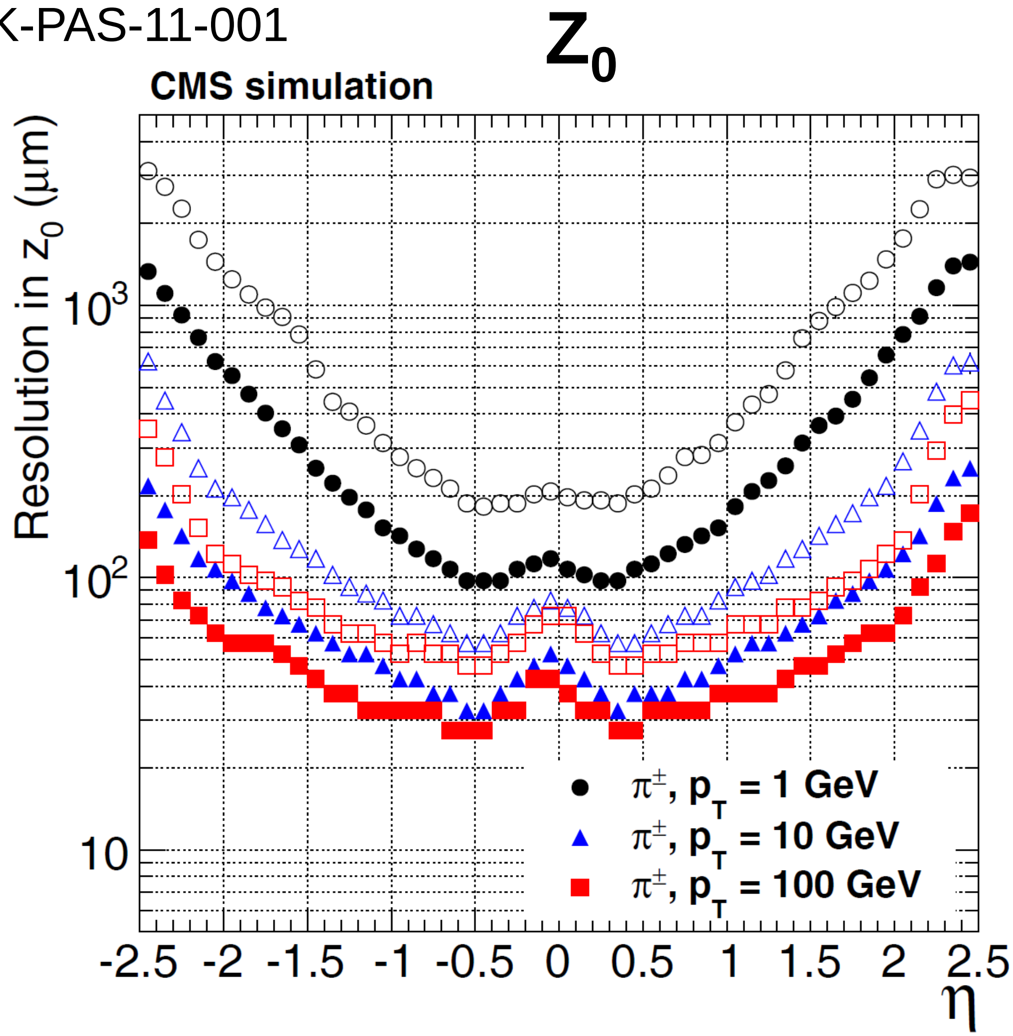
Large final state effect observed in PbPb collisions

Is the jet structure modified in PbPb collisions?

Charged Track Impact Parameter Resolution in pp

CMS TRK-PAS-11-001

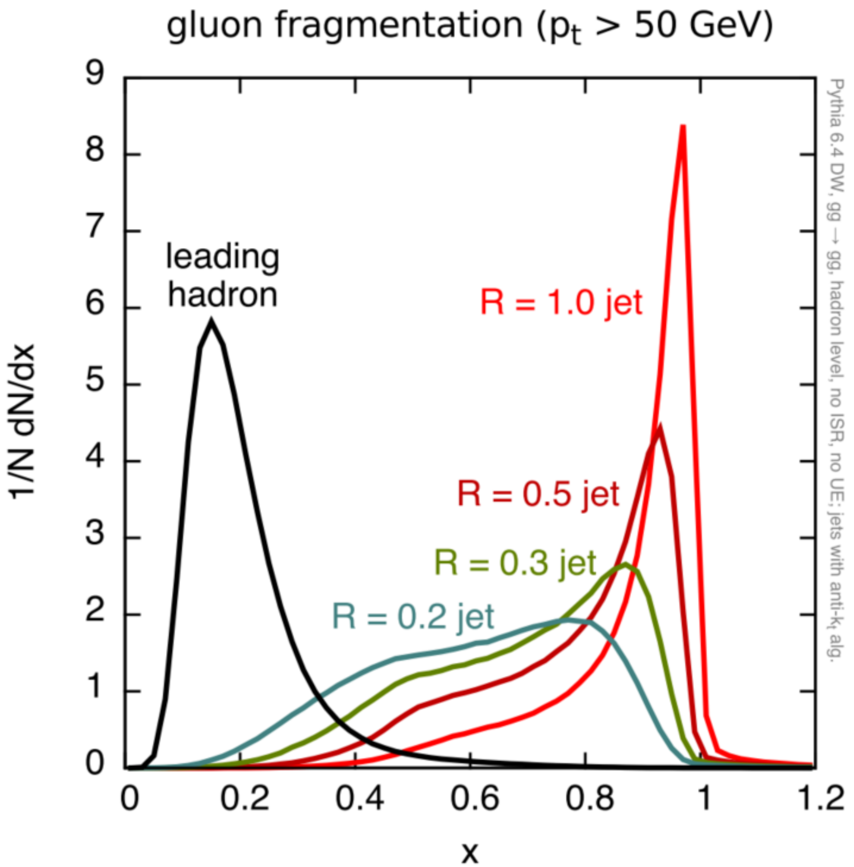




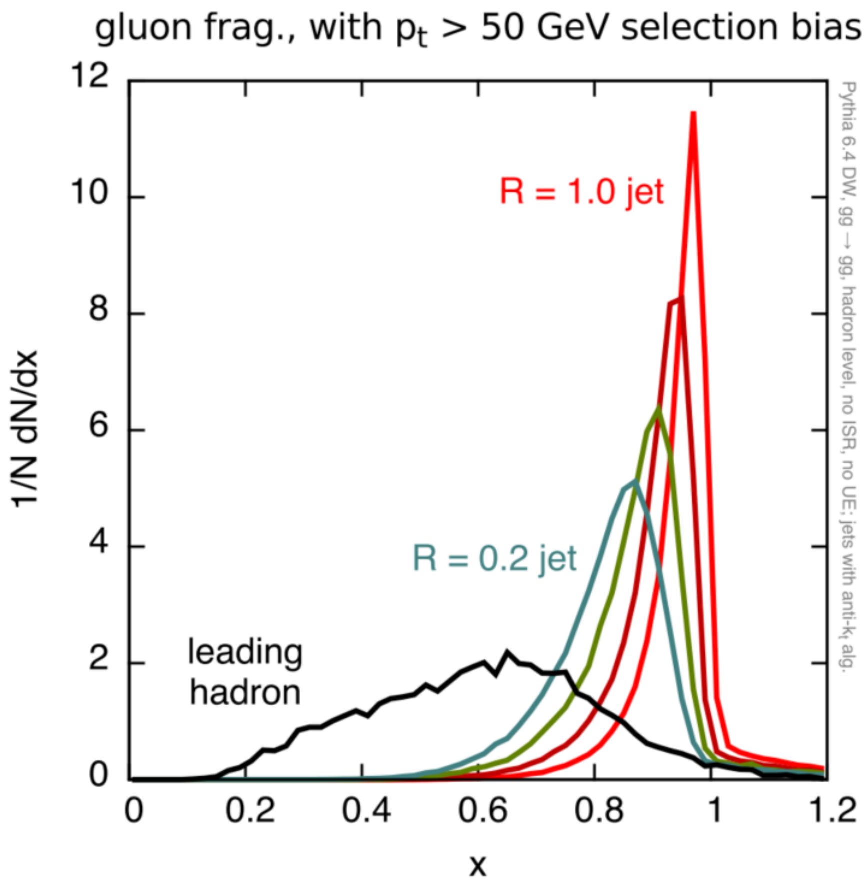
Track impact parameter resolution:

- d_0: ~80 μm @ 1 GeV/c, ~20 μm @ 10 GeV/c
- z_0: ~100 μm @ 1 GeV/c, ~40 μm @ 10 GeV/c

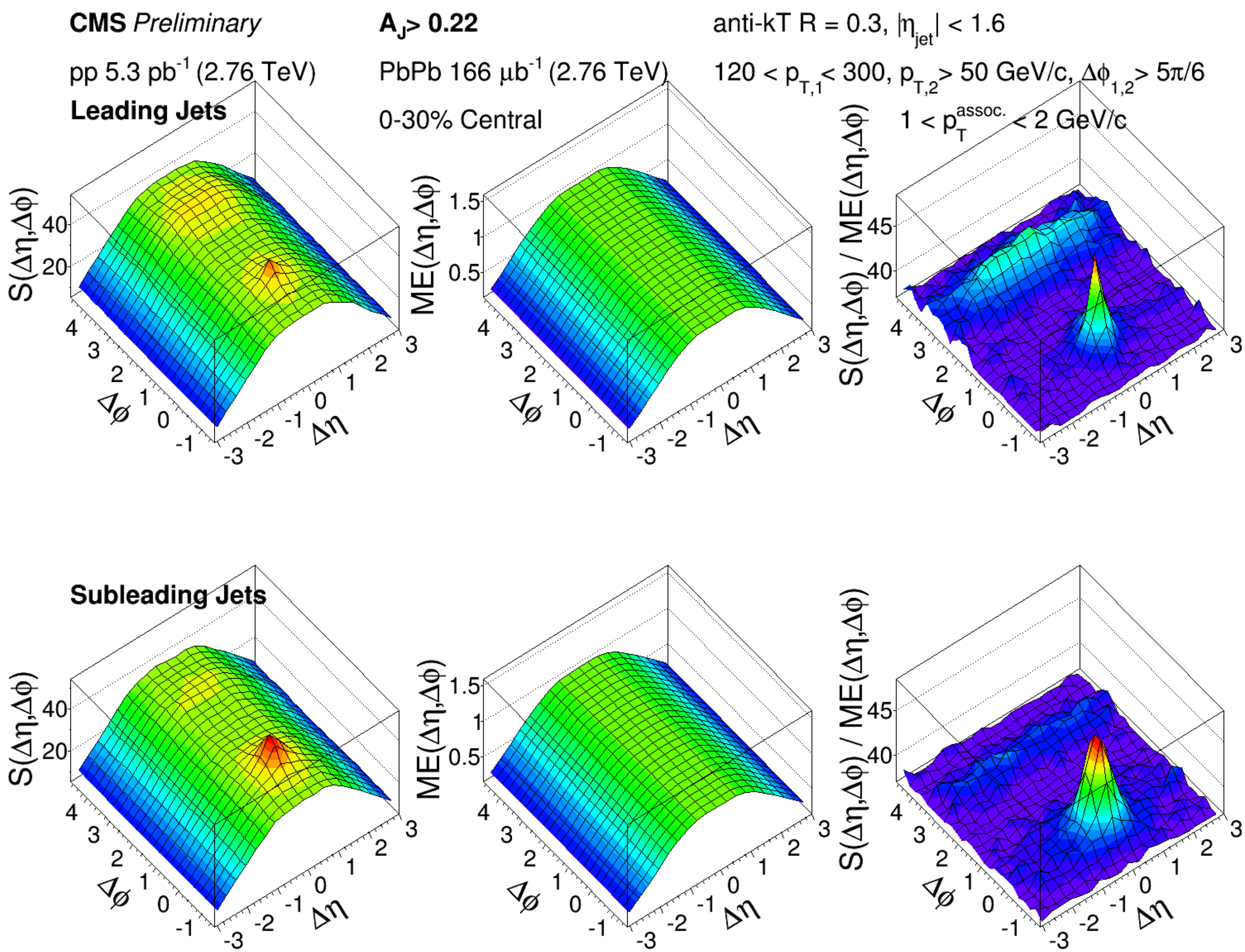
title



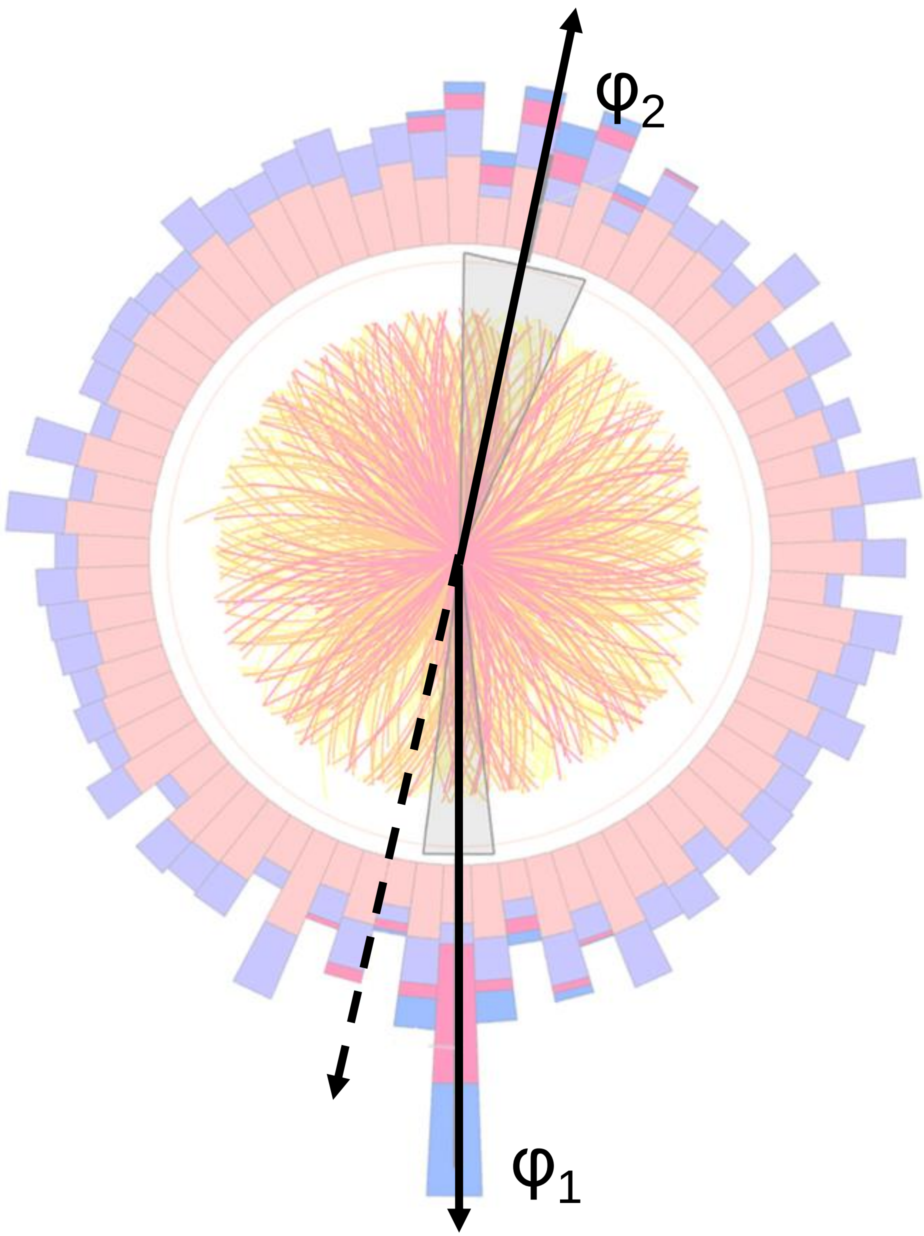
gluon fragmentation (p_t > 50 GeV)
leading hadron
R = 1.0 jet
R = 0.5 jet
R = 0.3 jet
R = 0.2 jet
1/N dN/dx
x
Pythia 6.4 DW, gg → gg, hadron level, no ISR, no UE; jets with anti-k_t alg.



gluon frag., with p_t > 50 GeV selection bias
R = 1.0 jet
R = 0.2 jet
leading hadron
1/N dN/dx
x
Pythia 6.4 DW, gg → gg, hadron level, no ISR, no UE; jets with anti-k_t alg.

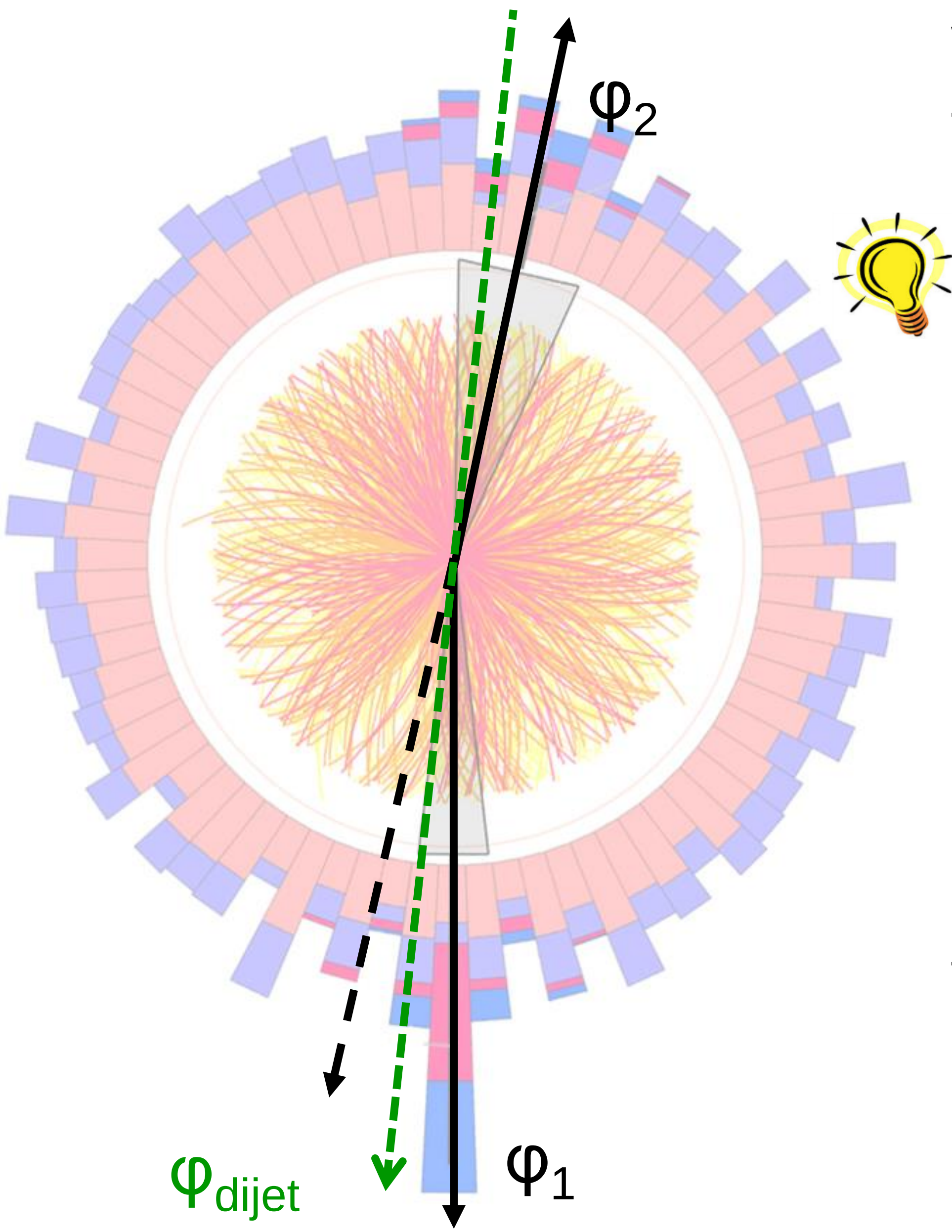

CMS Preliminary
A_J> 0.22
anti-kT R = 0.3, |η_jet| < 1.6
pp 5.3 pb^-1 (2.76 TeV)
PbPb 166 μb^-1 (2.76 TeV)
120 < p_T,1< 300, p_T,2> 50 GeV/c, Δφ_1,2> 5π/6
Leading Jets
0-30% Central
1 < p_T^assoc. < 2 GeV/c
S(Δη,Δφ)
ME(Δη,Δφ)
S(Δη,Δφ) / ME(Δη,Δφ)
Δφ
Δη
Subleading Jets

Multiplicity Difference



What is the **multiplicity** of the particles that balance the “extra” lost p_T?

Multiplicity Difference



What is the **multiplicity** of the particles that balance the “extra” lost p_T?

Compare the multiplicities in the leading and subleading jet hemispheres

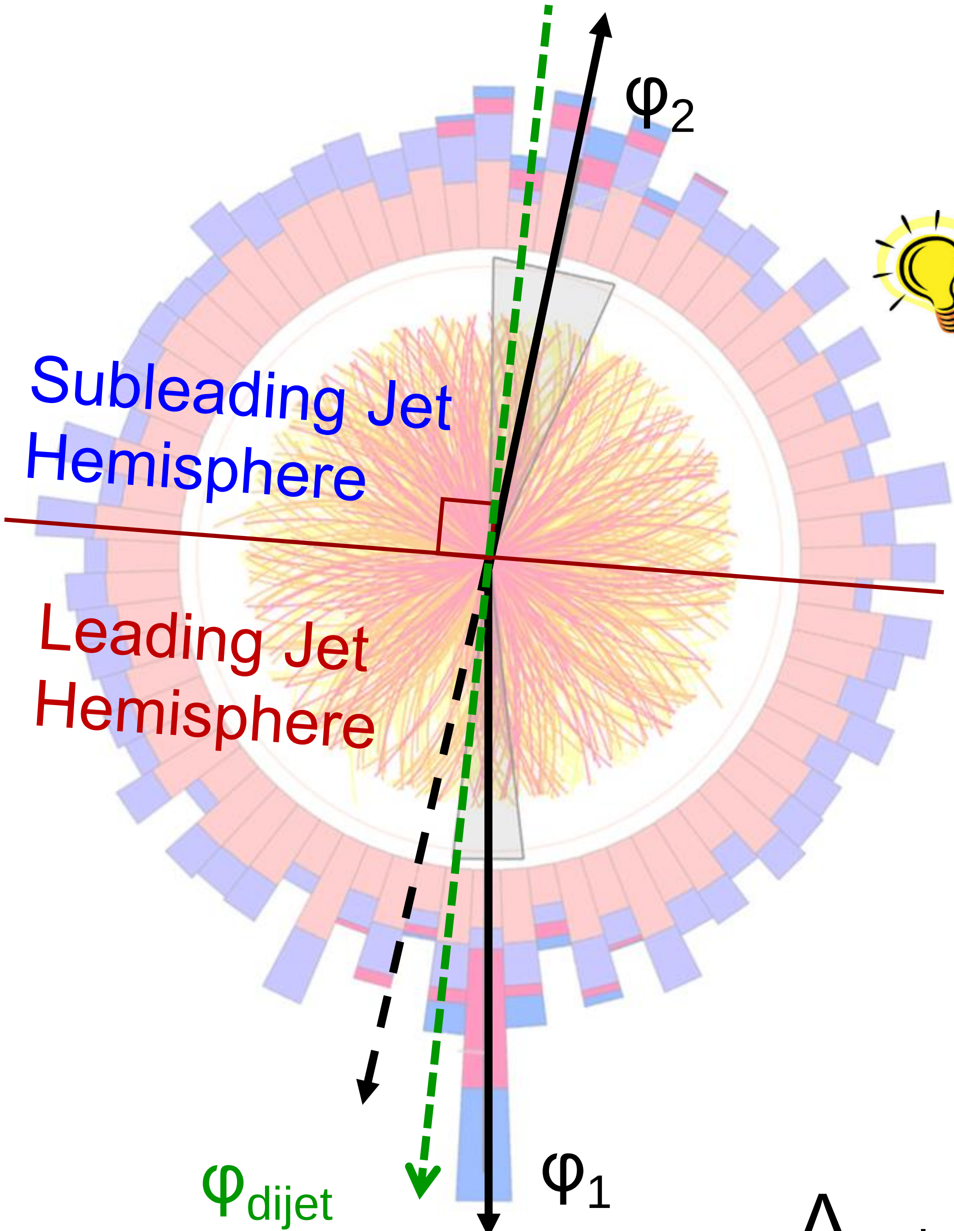
Direction of the dijet is defined as:

$$\varphi_{dijet} = \tfrac{1}{2}(\varphi_1 + (\pi - \varphi_2))$$

(In contrast to PRC 84 (2011) 024906, where the leading jet direction was used)

Provide UE cancellation differential in ΔR

Multiplicity Difference (subleading – leading jet)



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Provide UE cancellation differential in ΔR

Δ_{mult} = N_{ch} in **subleading** jet hemisphere - N_{ch} in **leading** jet hemisphere

Multiplicity Difference (subleading – leading jet)

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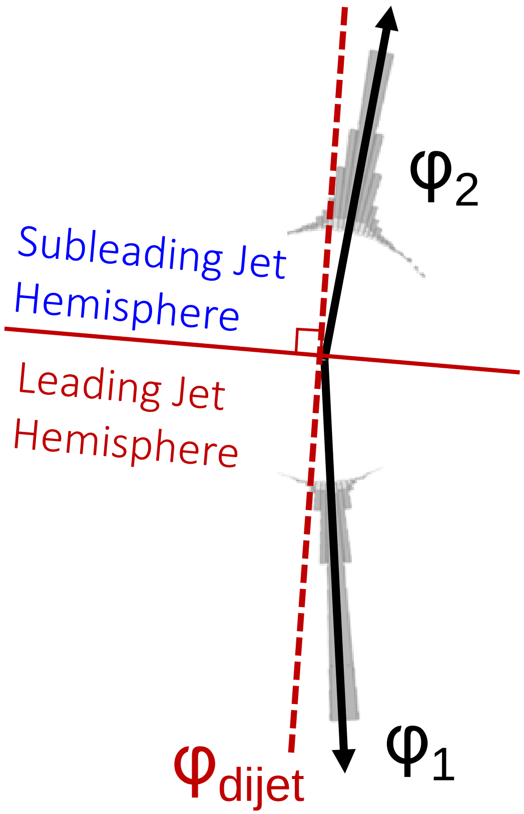
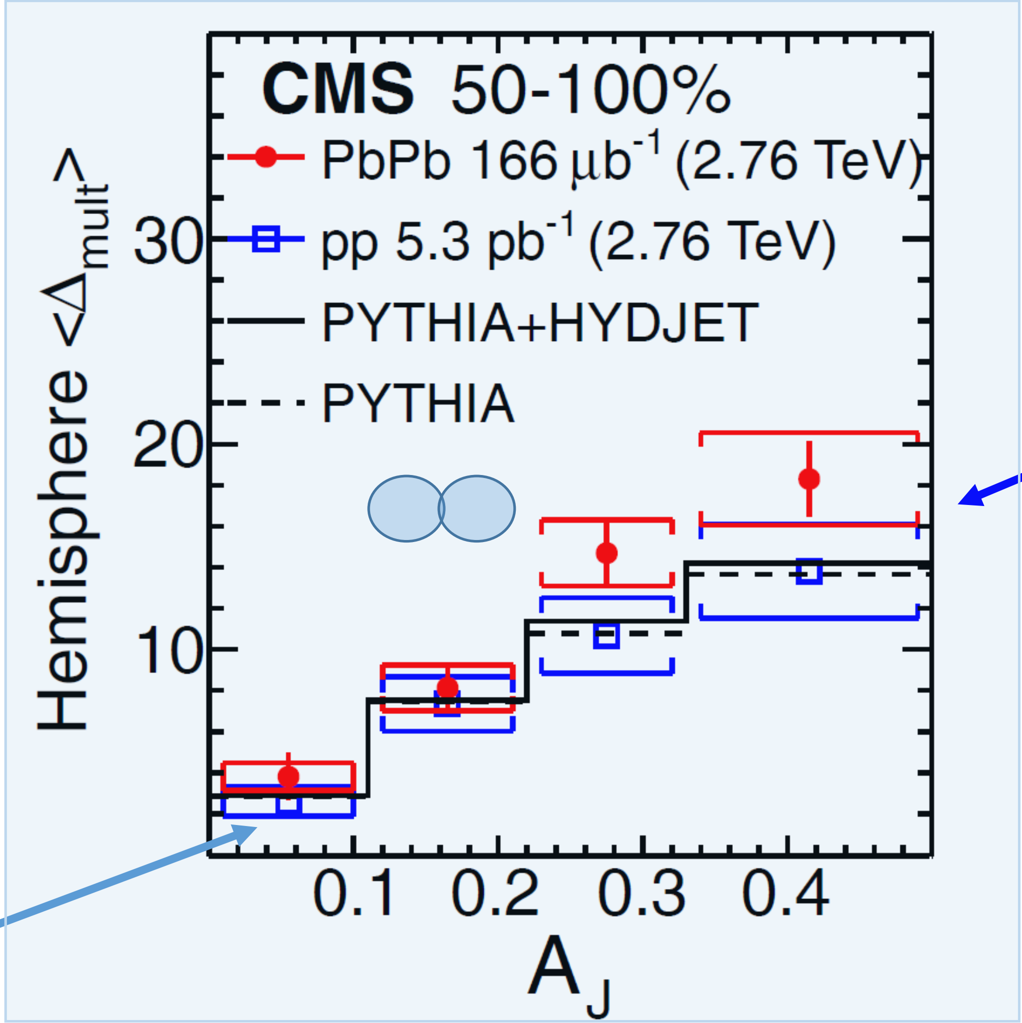
$\sqrt{s_{NN}}$ = 2.76 TeV



$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$



Three / multi-jet events

Symmetric Dijet Events

$\sqrt{s_{NN}}$=2.76 TeV

anti-k_T Calo R=0.3

$|\eta_{trk}| < 2.4$

$p_T^{trk} > 0.5$ GeV/c

Multiplicity difference between the **subleading** and **leading** hemisphere is increasing vs. dijet asymmetry in pp and peripheral PbPb.

There are more charged particles in the **subleading** hemisphere

Multiplicity Difference (subleading – leading jet)

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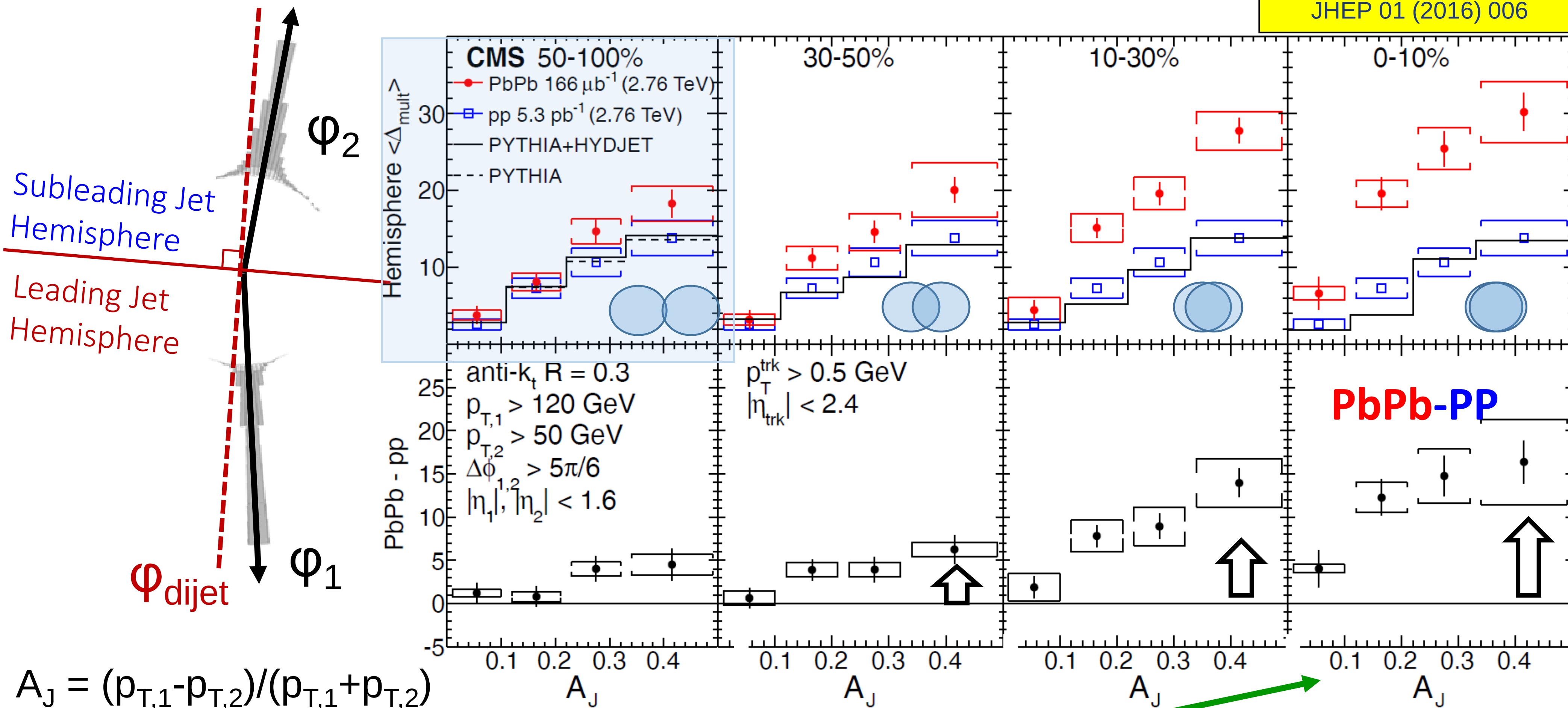
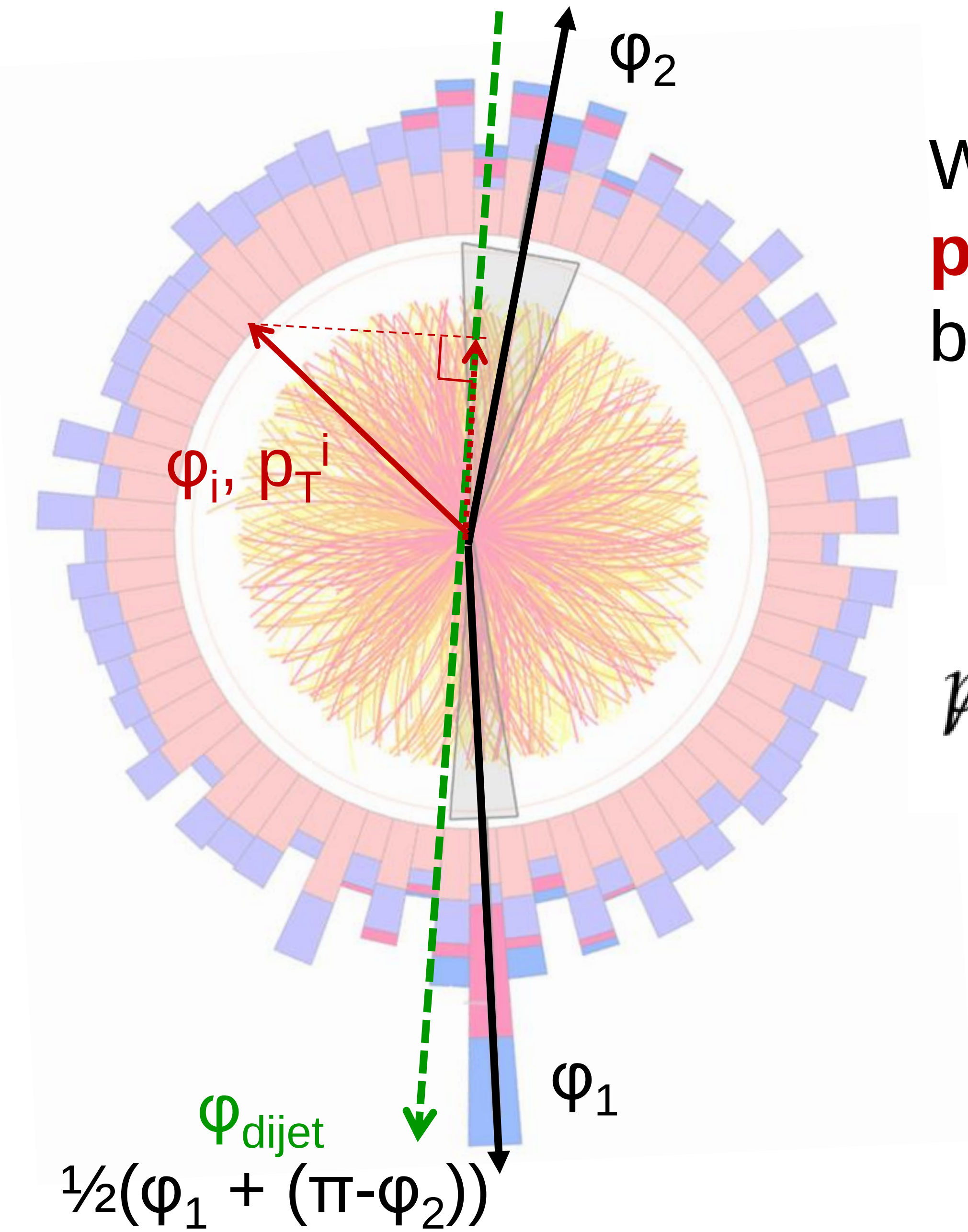


$A_J = (p_{T,1}-p_{T,2})/(p_{T,1}+p_{T,2})$

- **This increase is larger in central PbPb**
- The enhancement in PbPb compared to pp increases with centrality
  - Large A_J, 0-10%: ~**16 extra particles (p_T>0.5 GeV)** in the subleading jet hemisphere

Missing $p_T^{\parallel}$



What is the multiplicity and **p_T spectra** of the particles that balance the lost p_T?

Charged particle azimuthal angle

$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\mathrm{Dijet}}\right)$$

Dijet axis

Projection to dijet axis

Missing $p_T^{||}$ vs. A_J

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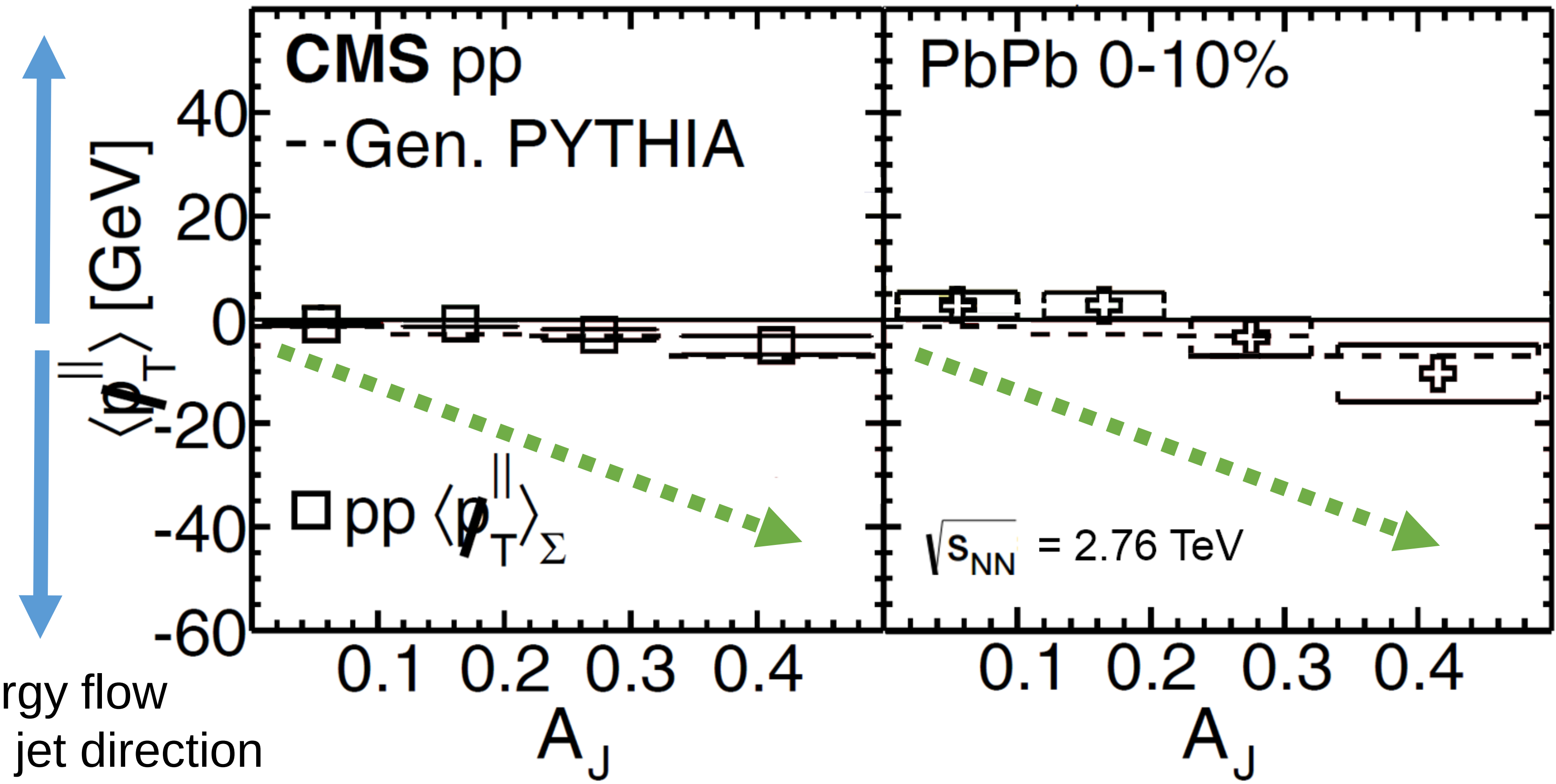
More energy flow
in the **subleading** jet direction

More energy flow
in the **leading** jet direction

PP **0-10% PbPb**



$p_{T,1}$>120, $p_{T,2}$>50 GeV/c
$|\eta_1|,|\eta_2|$<0.50, $\Delta\phi_{1,2}$>5π/6
anti-k_T Calo R=0.3

The momentum imbalance inside the jet cone is restored if we consider all particles in the event
(in both pp and PbPb collisions)

Missing $p_T^{||}$ vs. A_J

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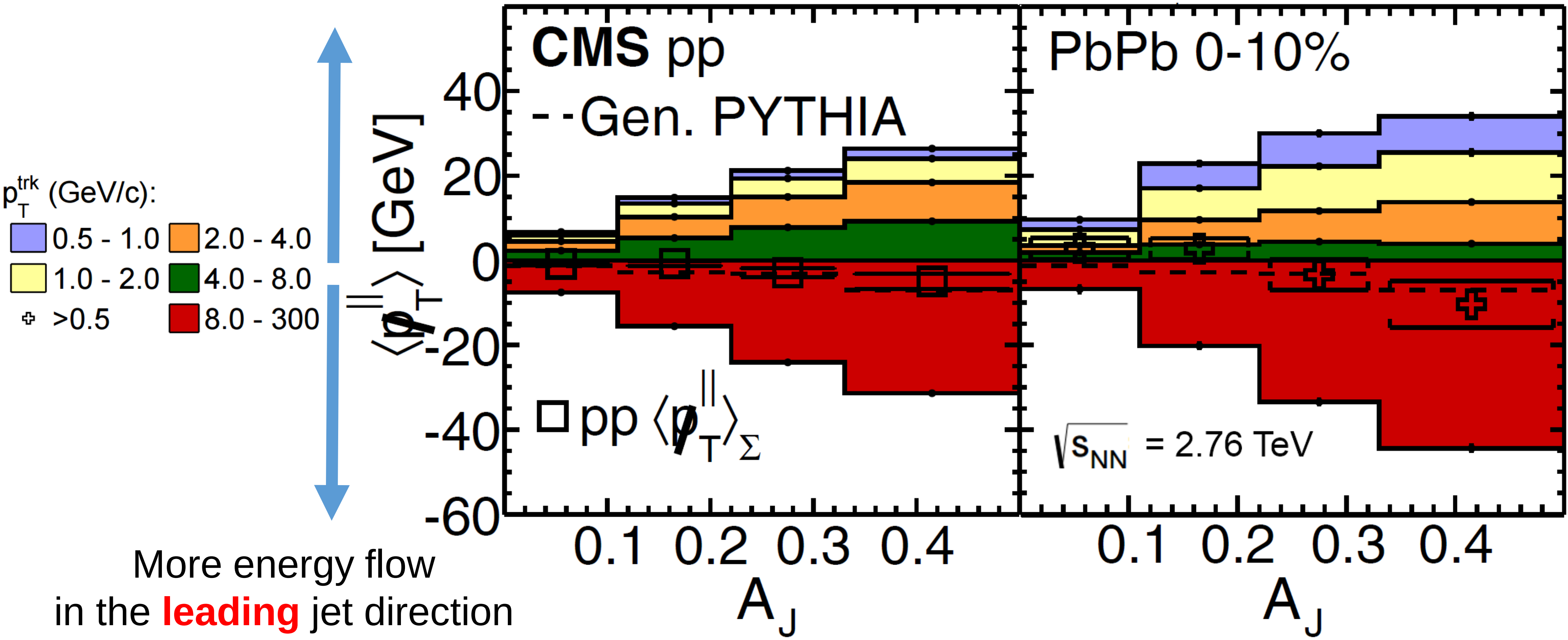
More energy flow in the **subleading** jet direction

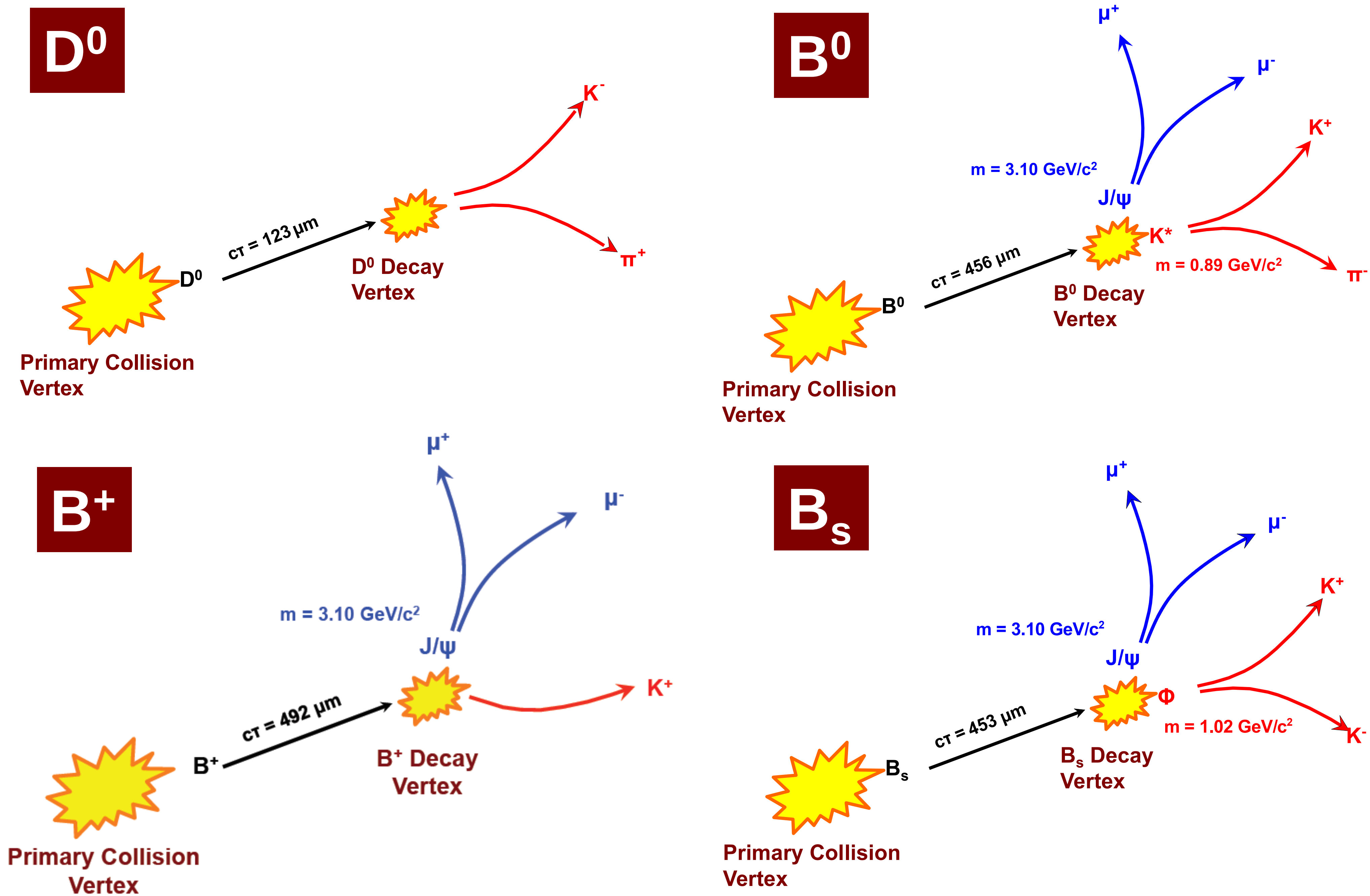
PP **0-10% PbPb**



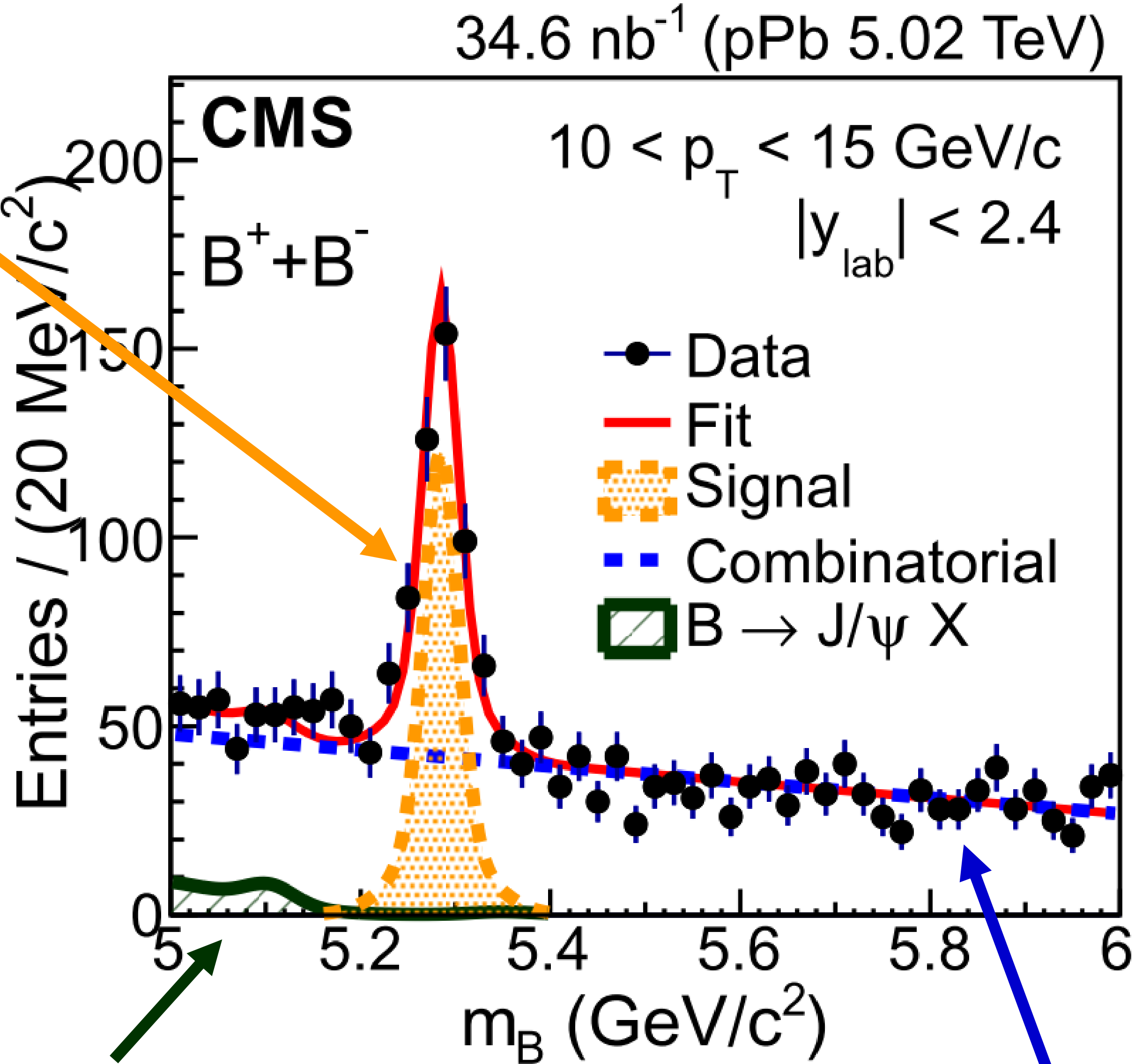
More energy flow in the **leading** jet direction

- Missing p_T from high p_T particles increases as a function of A_J
- In pp ⟶ Balanced by 2-8 GeV/c particles
- In 0-10% PbPb ⟶ Balanced by particles with p_T < 4 GeV/c

D and B Meson Decay Channels



B^+ Meson Mass Spectra in pPb



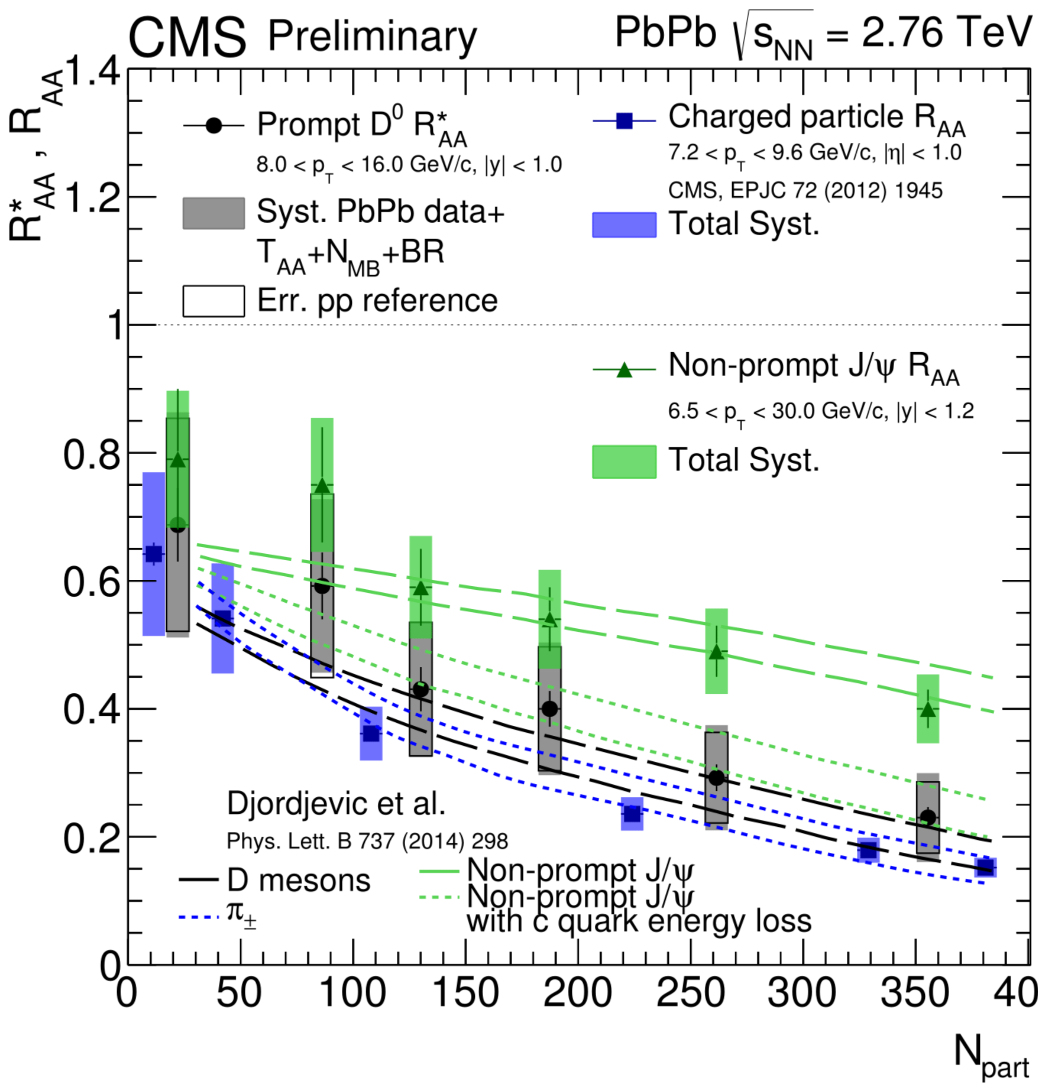
$B^+ \rightarrow J/\psi K^+$ signal

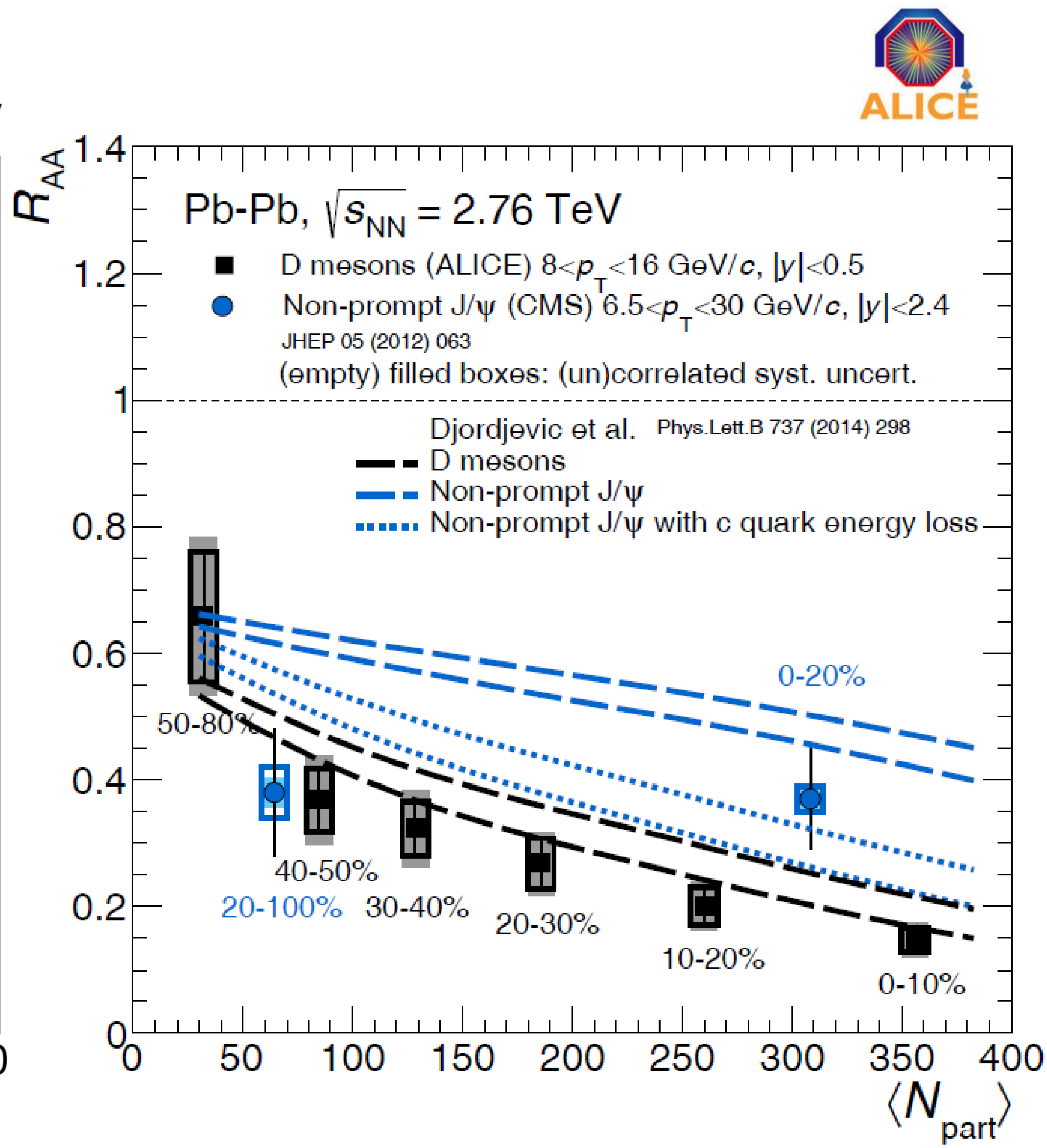
B+

Peaking background from $B \rightarrow J/\psi X$, for instance $B \rightarrow J/\psi K\pi$

Inclusive J/ψ + Track combinatorial background

Centrality Dependence (CMS vs. ALICE)

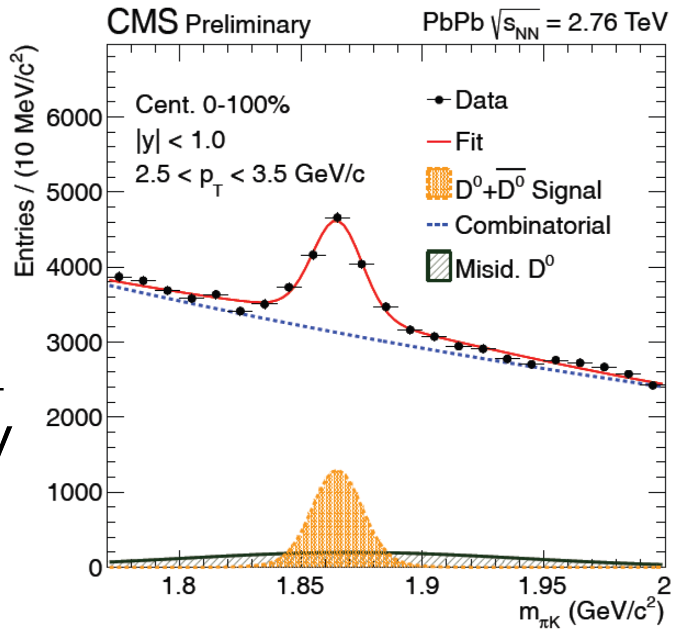




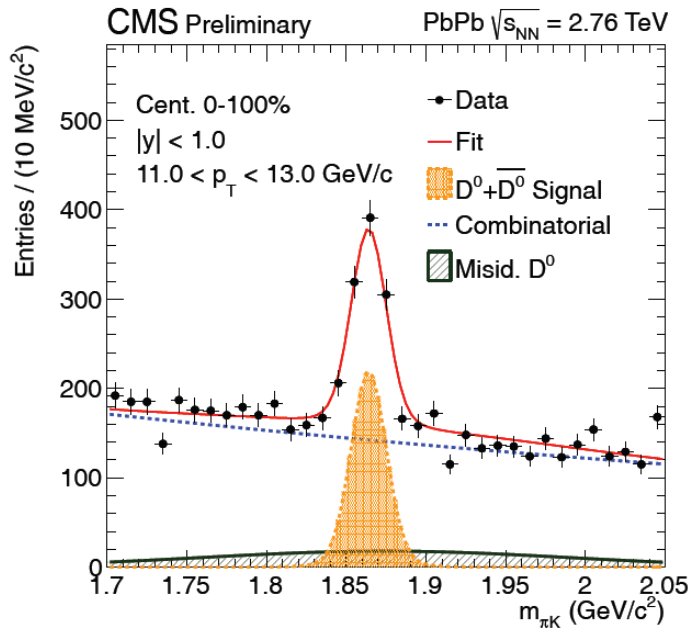
ArXiv 1506.06604

Clear D^0 Signal in p_T Range 2.5 to 40 GeV

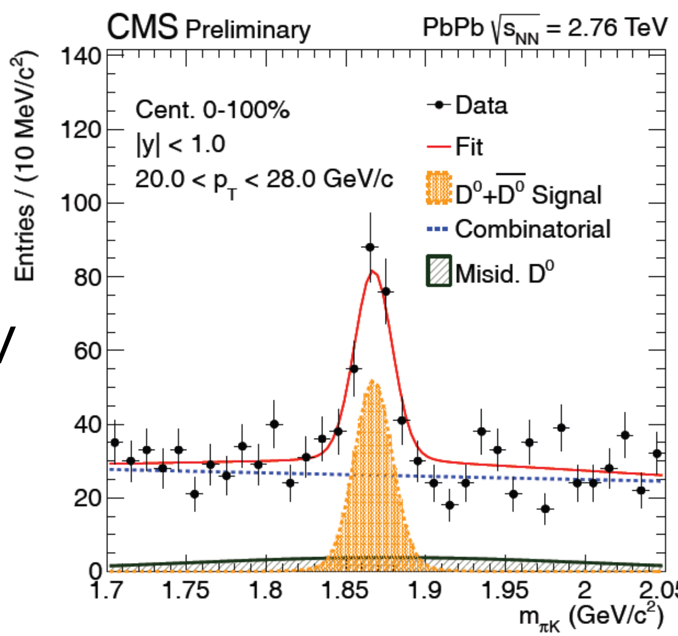
D meson p_T 2.5-3.5 GeV



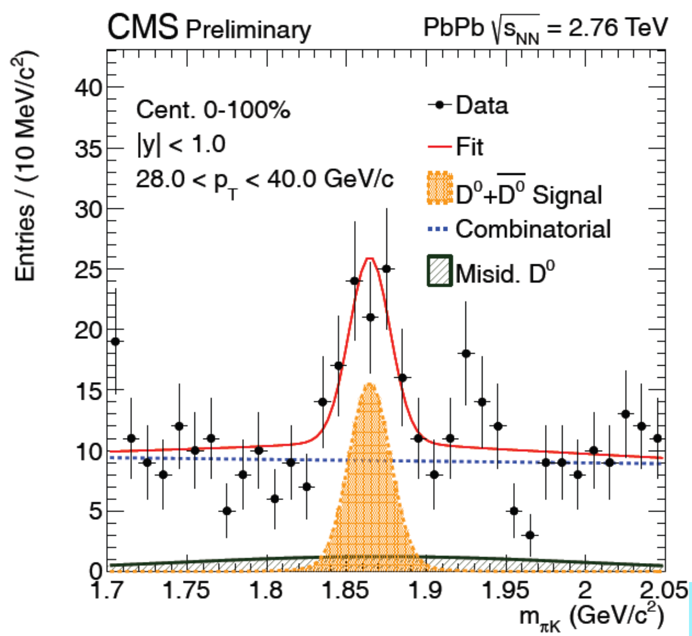
11-13 GeV



20-28 GeV

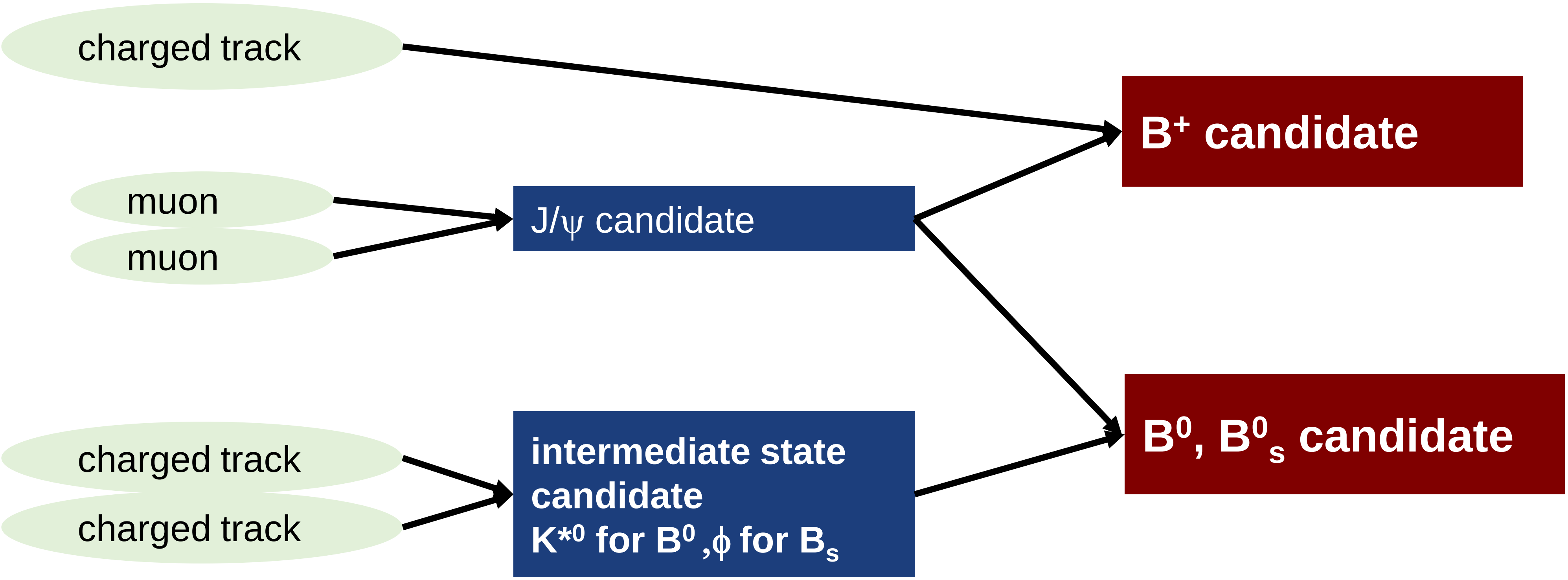


28-40 GeV



CMS PAS HIN-15-005

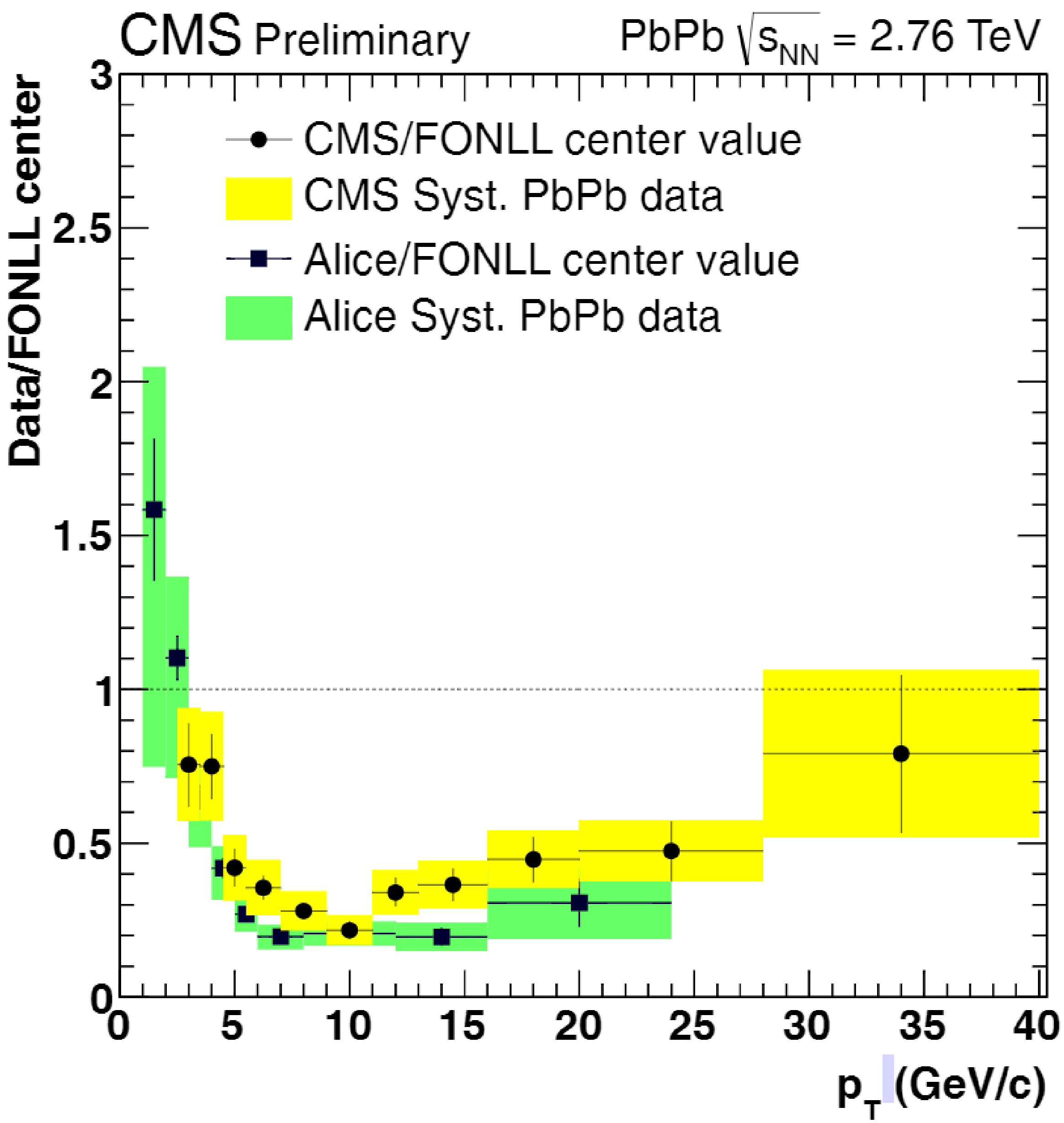
B Meson Reconstruction in CMS



- B^+ : J/ψ + 1 track (kaon, p_T> 0.9 GeV/c)
- B^0 : J/ψ + 2 tracks (kaon + pion, p_T>0.7 GeV/c)
- B_s : J/ψ + 2 tracks (kaon + kaon, p_T>0.4 GeV/c)

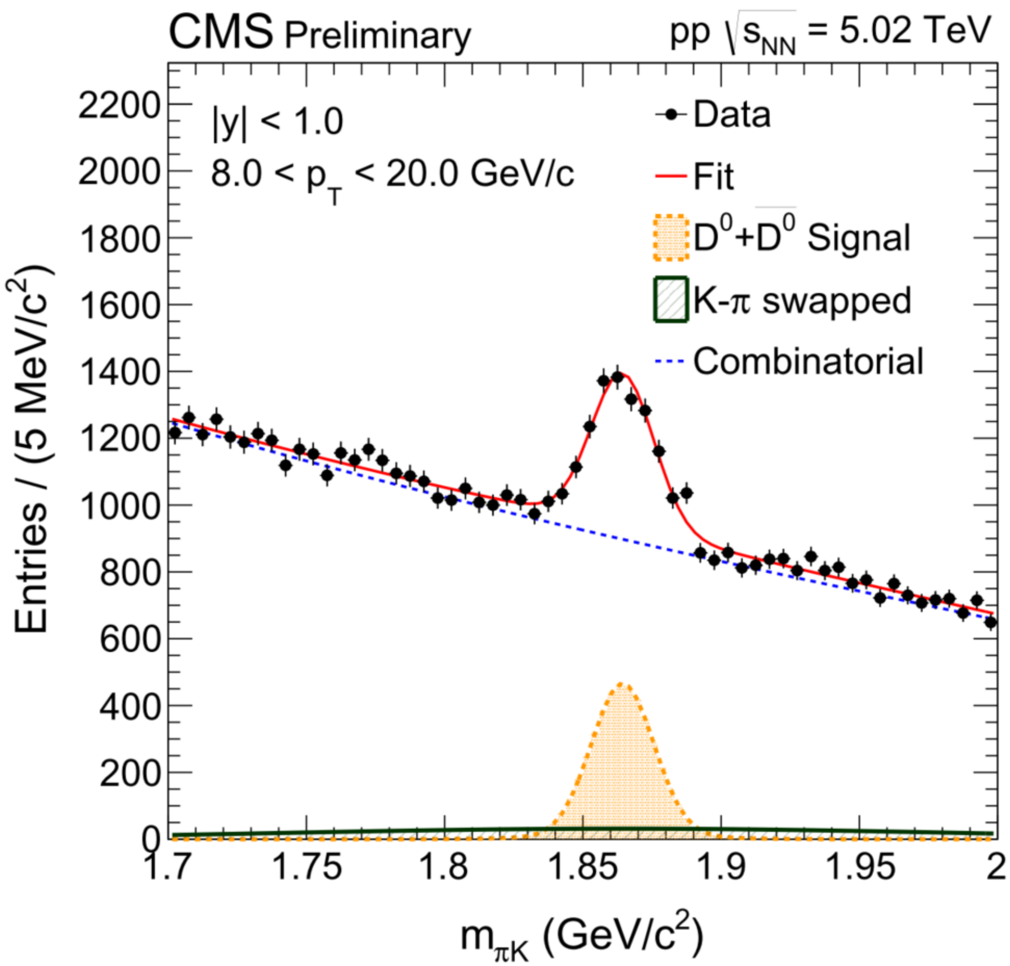
- Charged tracks and muons are reconstructed within $|\eta| < 2.4$
- Trigger muon p_T > 3 GeV/c
- No PID: Assigned the mass of kaon or pion to charged tracks

CMS vs. ALICE using FONLL as Reference



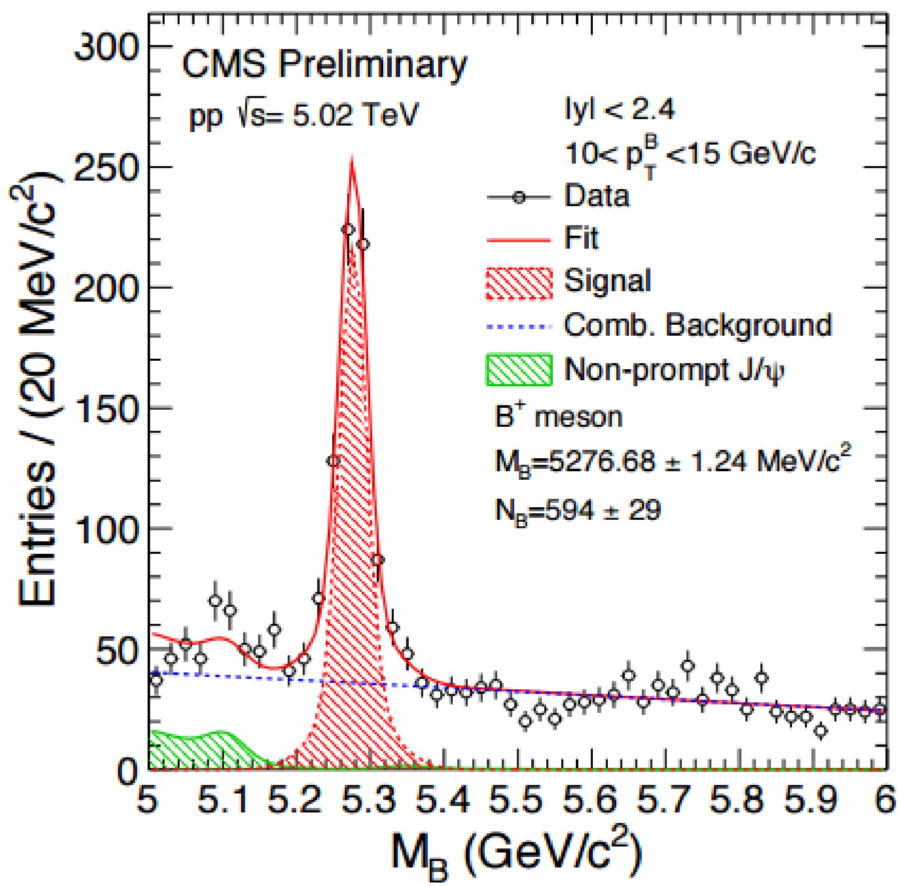
D^0 and B^+ peak in **proton-proton** collisions @ 5.02 TeV

D^0 mesons from online trigger



B^+ meson from dimuon triggered sample

$$B^+ \to J/\psi\, K^+ \to \mu^+\mu^- K^+$$



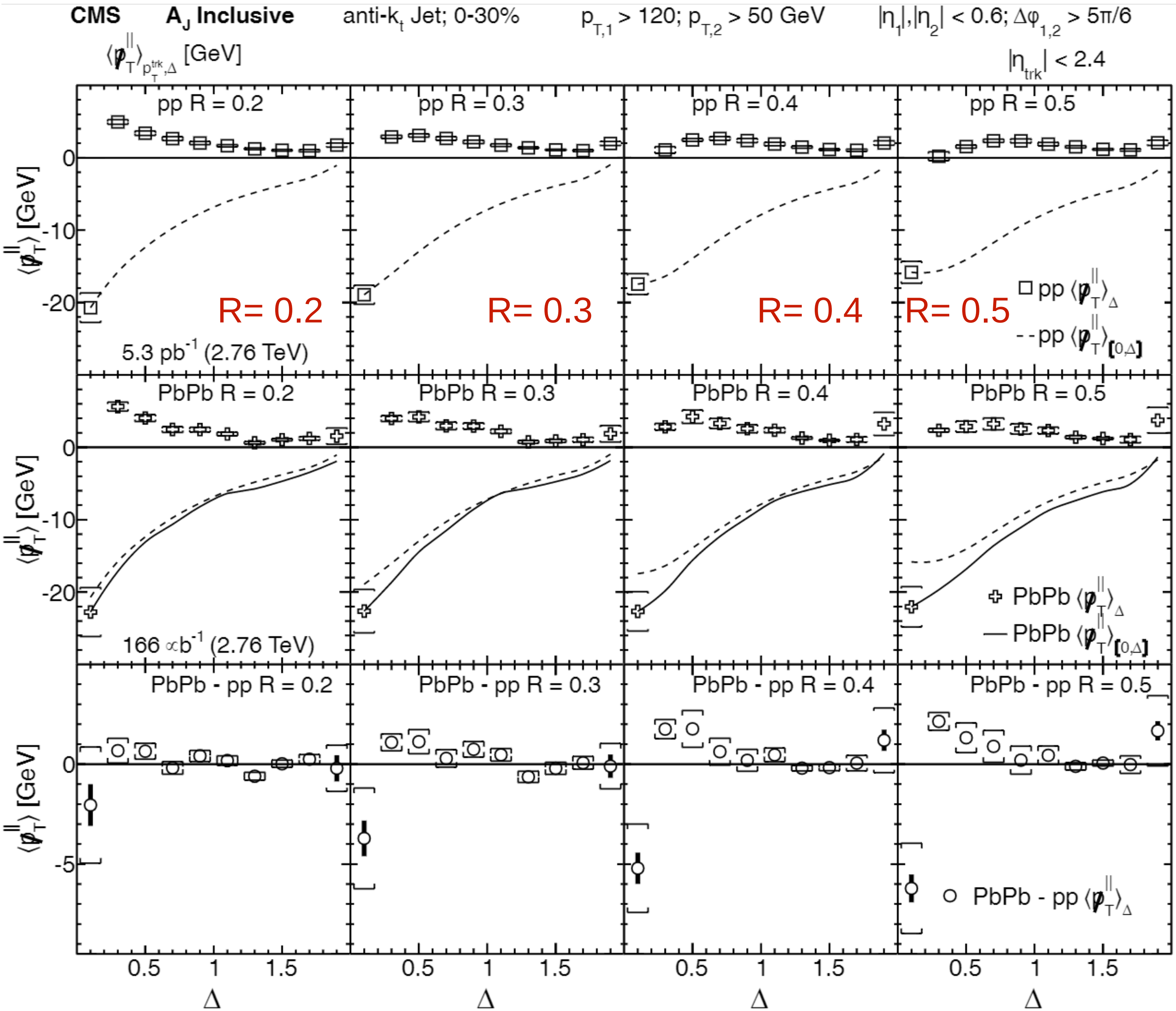
2.5 billion minimum-bias events recorded for low p_T D meson analyses (p_T<20 GeV/c). D^0 meson trigger for high p_T D^0 analyses (p_T> 8 GeV/c)

“Shooting Jets with Different Width” through the Medium

pp

PbPb

PbPb - pp



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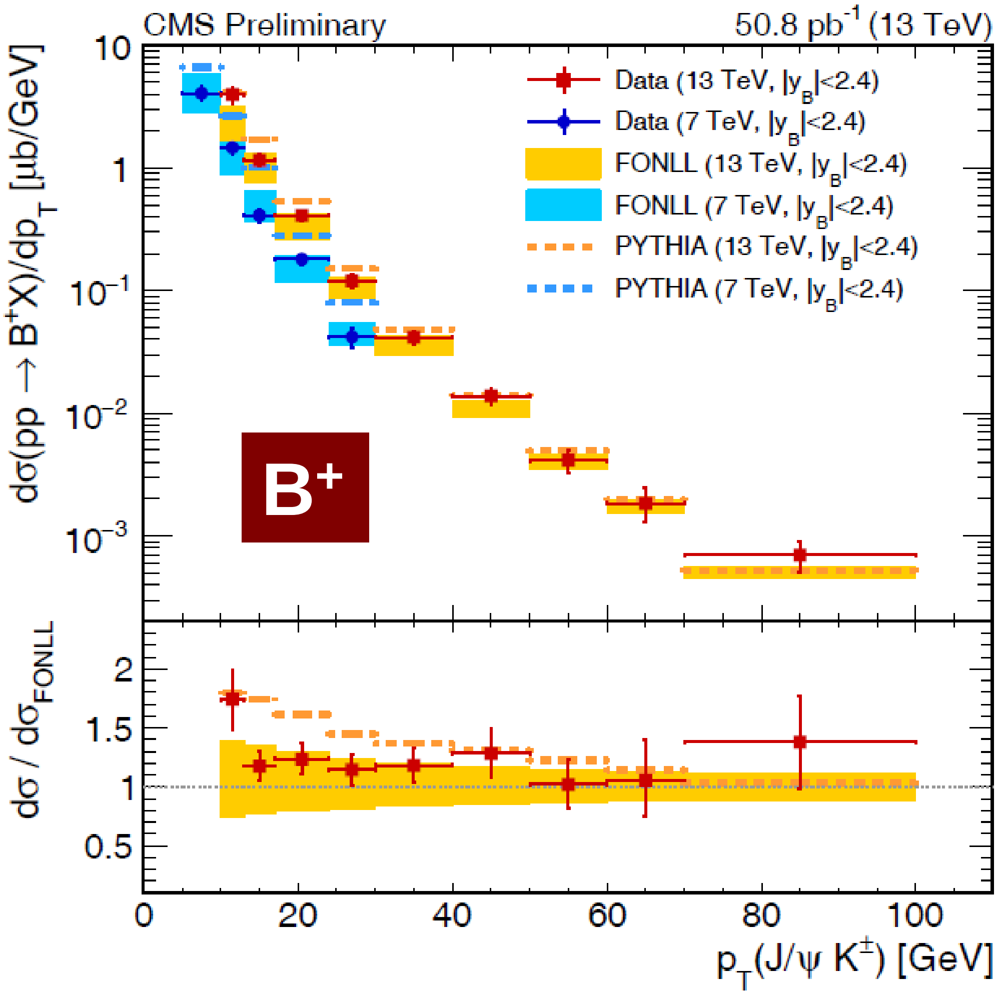
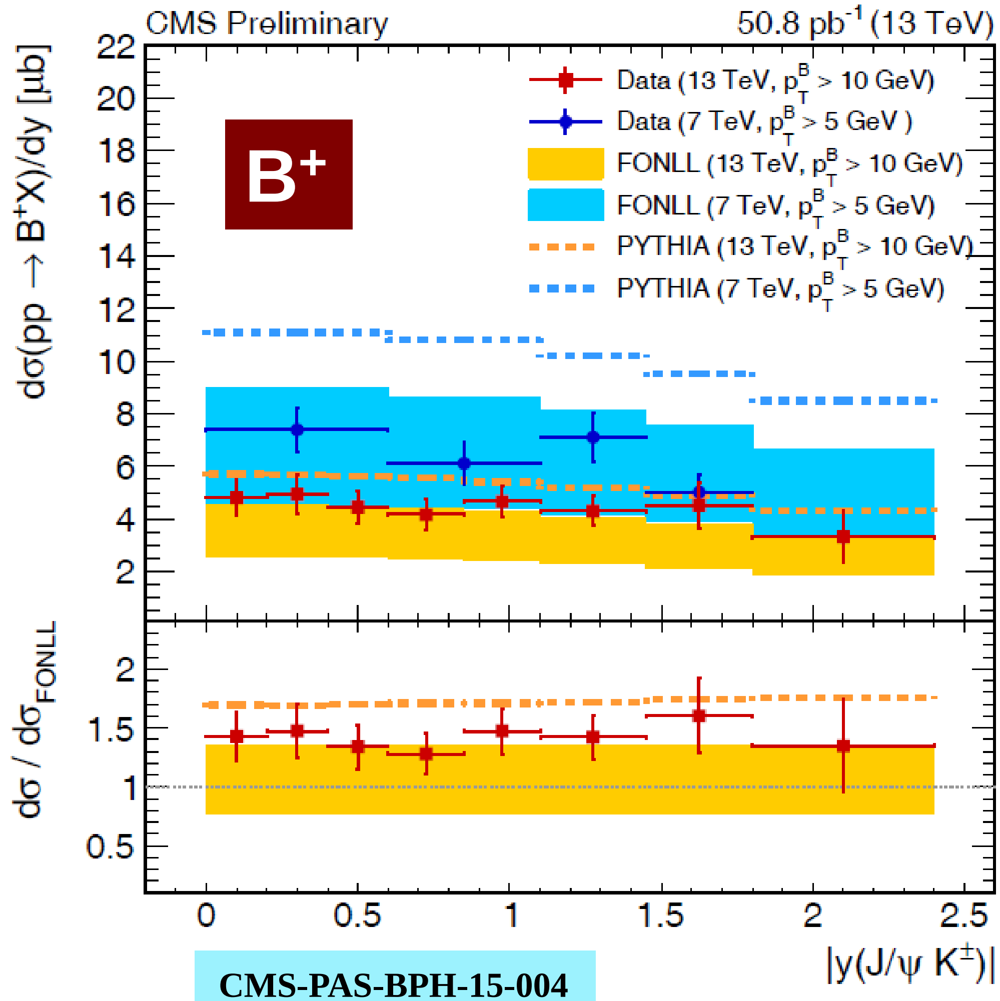
Results from pp @ 7 and 13 TeV

Transverse momentum spectra



Rapidity distribution



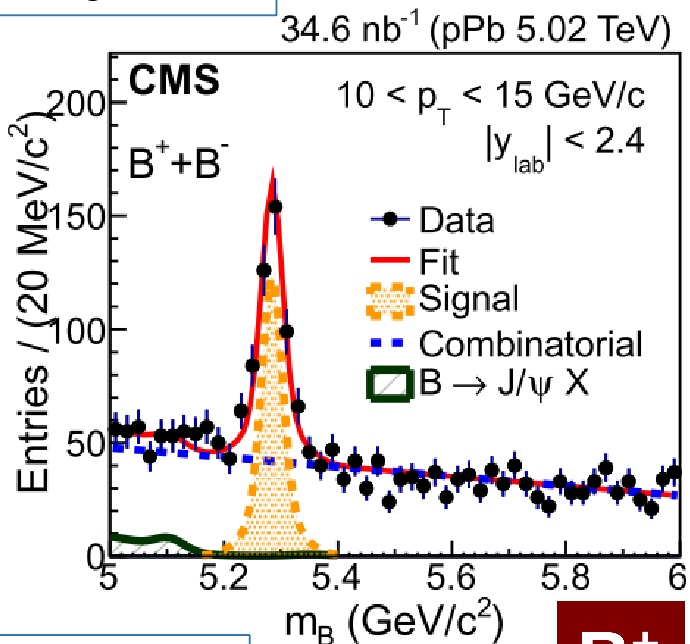
CMS-PAS-BPH-15-004

- pp at **7 TeV** and **13 TeV** are in agreement with FONLL calculation within the quoted uncertainties
- The central values of **7 TeV** data match better with FONLL center value than **13 TeV**

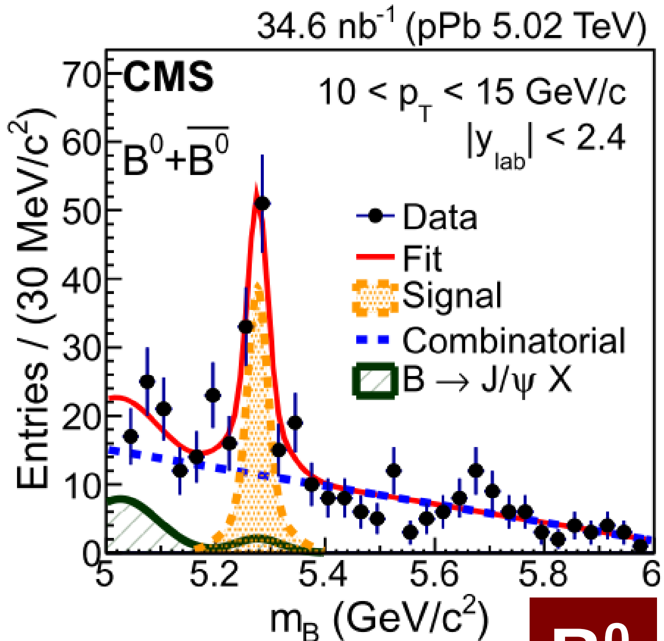
B Meson Mass Spectra in pp and pPb

pPb @ 5 TeV

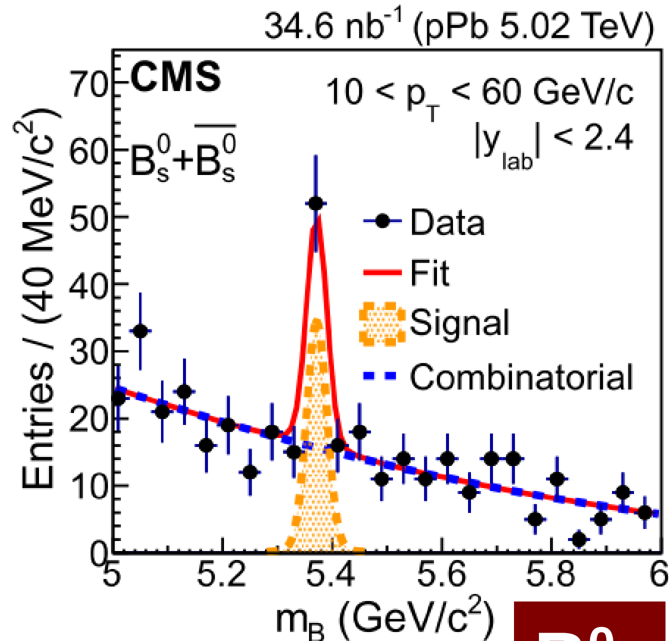
PRL 116 (2016) 032301



B^+

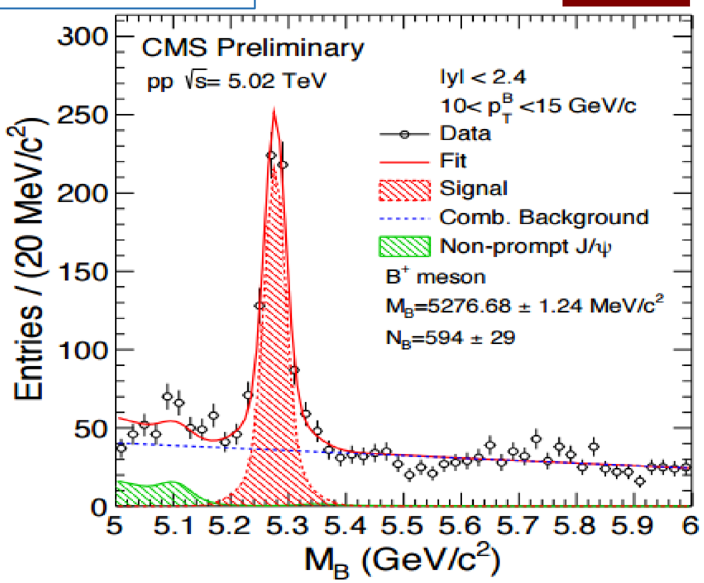


B^0



B^0_s

pp @ 5 TeV

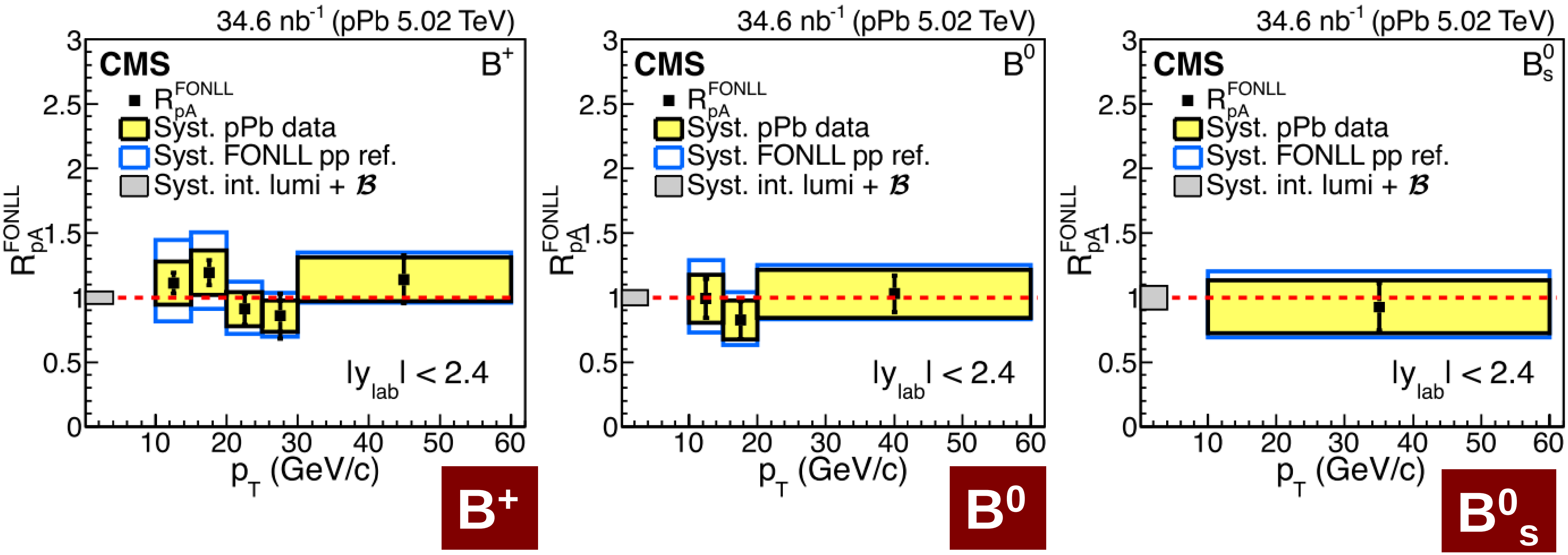


Significant B meson signal was observed in pp and pPb collisions

Nuclear Modification Factor : R_{pA}^{FONLL}

$$R_{pA}^{FONLL}(p_T) = \frac{\left(\frac{d\sigma}{dp_T}\right)_{pPb}}{A \times \left(\frac{d\sigma^{FONLL}}{dp_T}\right)_{pp}}$$

PRL 116 (2016) 032301



- R_{pA}^{FONLL} is compatible with unity within given uncertainties for three B mesons
- pp reference data at 5 TeV can significantly lower the systematical uncertainty